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Duty Cycle Characterization and Evaluation Towards Heavy Hybrid Vehicle Applications

Michael P. O'Keefe, Andrew Simpson, Kenneth J. Kelly
National Renewable Energy Laboratory

Daniel S. Pedersen
Oshkosh Truck Corporation

ABSTRACT

Four metrics related to vehicle duty cycle are derived from the energy equation of vehicle motion. Three key application areas are introduced. The first is the ability to quantify the sameness between vehicle duty cycles and the ability to asses a duty cycle's suitability for hybrid vehicle usage. The second area of application allows for the estimation of fuel consumption for a given vehicle over a target duty cycle. The third area of application allows us to predict how non-propulsion fuel use will affect energy use. The paper ends with real-world examples involving actual heavy-duty hybrids.

INTRODUCTION

Hybrid electric technology is of great interest to users and manufacturers of heavy vehicles due to the technology's ability to reduce fleet fuel consumption and emissions. Challenges still exist for hybrid technology in terms of purchase and life-cycle cost, testing, packaging, durability, and reliability. However, independent from the challenges of hybrid technology itself is the question of when and where do hybrids make sense and what are the benefits of hybridization for a given application. Because heavy vehicles often operate as critical elements to a business model, the hybrid value equation often depends on reduced in-use fuel consumption in order to justify the added purchase cost over a conventional vehicle. Thus, it is often critical that hybrid vehicles be deployed over duty cycles where they will show a clear benefit.

There are a wide variety of heavy vehicle vocations applicable to hybridization including refuse haulers, transit buses, pick-up and delivery vehicles, utility trucks, and military applications. The variation between heavy vehicle vocations is large though the variation within a vocation is typically significant as well. Thus, it is important for those evaluating hybrids as a purchase option and for those manufacturing hybrids to understand the duty cycle of the intended application.

A duty cycle provides a concise, repeatable sequence of vehicle input operations over some time period. A typical duty cycle consists of second-by-second values of speed and elevation, though time-based information on the operation of other systems is sometimes included as well. Duty cycles are most valuable when they are representative of how a vehicle will operate in a target application. However, whether or not a cycle is representative can be a challenge to determine.

Creation of representative cycles from test data is no easy task. This is especially true for heavy vehicles as the duty cycle must account for more than just vehicle speed and elevation versus time (as in light-duty applications). In heavy-vehicle applications, cargo weight, road-surface, route type, and vocational loads (such as trash compaction on a refuse hauler) can vary dramatically over time. The choice of the term "duty cycle" as opposed to "drive cycle" is a conscious choice by the authors to emphasize that there is more to heavy-vehicle cycles than just the time-speed operation.

In this paper, we examine some physical-based metrics to aid the reader in duty cycle characterization and duty cycle evaluation with hybrid-electric vehicles in mind. We hope to better equip the reader to determine the applications where hybrids will make the most sense.

MAIN SECTION

It is well known that vehicle energy usage is closely linked with duty cycle [1, 2, 3]. This is especially true for hybrid-electric vehicles. Therefore, insight can be gained from understanding the physical mechanisms of how vehicle energy use relates to the duty cycle.

We will therefore begin by examining the energy usage equation as applied to heavy vehicles. The energy equation will form the basis for a discussion of physical-based metrics—metrics derived directly from the energy equation and holding a physical significance. Examples of how the metrics can be used to characterize and evaluate cycles for hybrids will be presented. We will end by discussing some heavy-vehicle applications of the metrics. The metrics themselves are an extension of the work done by [1]. The reader is directed there for a more in-depth background and derivation.

UNDERSTANDING HEAVY VEHICLE ENERGY USAGE

The tractive power required to move a vehicle over a roadway surface is the summation of the power required to overcome:

1. Aerodynamic drag
2. Rolling resistance
3. Vehicle inertia
4. Gravitational potential energy.

This is given by the classic roadload equation for power presented below [4]:

Equation 1:

$$
\begin{aligned}
P_{road} = & \frac{1}{2} \cdot \rho \cdot C_D \cdot FA \cdot v^3 \\
& + RRC_0 \cdot M_{veh} \cdot g \cdot v \\
& + M_{veh} \cdot v \cdot \frac{dv}{dt} \\
& + M_{veh} \cdot g \cdot \frac{dh}{dt}
\end{aligned}
$$

Positive values of power indicate a tractive effort from the vehicle while negative values indicate the need for power absorption by the vehicle powertrain. This power absorption can occur by various means such as mechanical brakes or as part of a regenerative braking system. Equation 1 can be integrated over time and discretized to determine the energy required over some finite time period, or time step, t_j to t_{j+1}, as follows:

Equation 2:

$$
\begin{aligned}
E_{road,j,j+1} = & \frac{1}{2} \cdot \rho \cdot C_D \cdot FA \cdot \overline{v^3_{j,j+1}} \cdot \Delta t_{j,j+1} \\
& + RRC_0 \cdot M_{veh} \cdot g \cdot \overline{v_{j,j+1}} \cdot \Delta t_{j,j+1} \\
& + \frac{1}{2} \cdot M_{veh} \cdot (v^2_{j+1} - v^2_j) \\
& + M_{veh} \cdot g \cdot \Delta h_{j,j+1}
\end{aligned}
$$

In equation 2, it is assumed that speed and elevation vary linearly over each time step. With this assumption, the following additional terms can be defined as:

Equation 3:

$$
\begin{aligned}
\Delta t_{j,j+1} &= t_{j+1} - t_j \\
\Delta h_{j,j+1} &= h_{j+1} - h_j \\
\overline{v_{j,j+1}} &= \frac{v_{j+1} + v_j}{2} \\
\overline{v^3_{j,j+1}} &= \frac{v^3_{j+1} + v^2_{j+1} \cdot v_j + v_{j+1} \cdot v^2_j + v^3_j}{4}
\end{aligned}
$$

The fuel energy required over any given time period will be a summation of:

1. The fuel to satisfy tractive effort (adjusted by the application of supplemental power from a hybrid energy storage system)
2. Fuel to charge the hybrid electric system
3. Fuel to satisfy vocational loads (e.g., hotel loads, trash compaction, boom operation, etc.)
4. The fuel used when the vehicle is idle. Idle is defined in this paper as when the vehicle is stopped and not performing useful work (i.e., not generating vocational load power) but is still "on".

This can be summarized in equation form as follows:

Equation 4:

$$
\begin{aligned}
E_{fuel,j,j+1} = & \frac{E_{road,j,j+1} - E_{\text{supplemental},j,j+1}}{\overline{\overline{\eta_{powertrain,j,j+1}}}} \\
& + \frac{\overline{\overline{E_{charge,j,j+1}}}}{\eta_{charge,j,j+1}} + E_{fuel,voc,j,j+1} + E_{fuel,idle,j,j+1}
\end{aligned}
$$

To accurately use equation 4 requires knowledge of how each of the terms varies with time over the duty cycle. Let us reduce the number of terms in equation 4. Some fraction of the available regenerative energy from the cycle can be captured and redeployed via the hybrid energy storage system. This will allow us to eliminate the $E_{supplimental}$ term from equation 4. To reduce the number of terms further, the powertrain efficiency term can be adjusted using the following concept:

Equation 5:

$$
\begin{aligned}
& C = \frac{a}{\eta^*} + b \rightarrow C = \frac{a}{\eta} \text{ for any } a \neq 0 \\
& \eta^* = \frac{a}{C-b}, \eta = \frac{a}{C}
\end{aligned}
$$

Applying the concept in equation 5 to equation 4 yields equation 6 which assumes the following:

- Equation 6 is written for the entire cycle fuel usage where equation 4 applies to a single time step
- The supplemental energy term is rewritten using the cycle's available regenerative energy ($E_{road,neg}$) and a regen capture and redeployment efficiency (η_{regen})
- The total tractive effort is expressed as $E_{road,pos}$
- equation 5 is applied to the cycle averaged power-train efficiency to incorporate charging energy
- The fuel energy associated with vocational loads is combined with the fuel energy associated with idle and called $E_{fuel,other}$.

This yields:

Equation 6:

$$E_{fuel} \cong \frac{E_{road,pos} + E_{road,neg} \cdot \overline{\eta_{regen}}}{\overline{\eta_{powertrain}}} + E_{fuel,other}$$

with the following terms defined as:

Equation 7:

$$E_{road,pos} = \sum_{j=1}^{N-1} positive(E_{road,j,j+1})$$

$$E_{road,neg} = \sum_{j=1}^{N-1} negative(E_{road,j,j+1})$$

where *positive* and *negative* are defined as:

Equation 8:

$$positive(x) = u(x) \cdot x :$$

$$u(x) = \begin{cases} 0, x < 0 \\ 1, x \geq 0 \end{cases}$$

$$negative(x) = q(x) \cdot x :$$

$$q(x) = \begin{cases} 0, x > 0 \\ 1, x \leq 0 \end{cases}$$

The advantage of writing the fuel usage equation this way is that we now have terms that are either known from the duty cycle and vehicle parameters ($E_{road,pos}$, $E_{road,neg}$), or can be measured or estimated ($E_{fuel,other}$, $\eta_{powertrain}$, η_{regen}). Note that equation 6 is specific to the duty cycle and vehicle under consideration.

As an example of how measurement could be used to determine the terms in equation 6, consider the following designed experiments conducted using an arbitrary duty cycle and a chassis dynamometer.

Table 1: Designed Experiments

Experiment	**Term(s)**
calculation from duty cycle (speed, time, and elevation only) and vehicle metrics	$E_{road,neg}$ and $E_{road,pos}$
measure fuel over the duty cycle with all vocational loads off and idle portions removed, regen disabled	$\eta_{powertrain}$
measure fuel consumption over the duty cycle with all vocational loads off and idle portions removed, regen enabled	η_{regen}
measure the fuel consumption over the full duty cycle with regen enabled	$E_{fuel,other}$

We can make further strides if we realize that the terms of the roadload equation can be separated into duty-cycle specific values and vehicle specific values.

Let us start by converting the relation for the tractive energy required at the road, E_{road}, to *specific energy per distance* (SEPD). This relation is given as follows:

Equation 9:

$$SEPD = \frac{E}{M_{veh} \cdot D} \equiv \text{specific energy per distance}$$

Equation 10:

$$SEPD_{road,j,j+1} = C_{aero} \cdot v_{aero,j,j+1}^2 + C_{rolling} + \tilde{a}_{j,j+1}$$

Equation 10 uses two sets of parameters: one set only dependent on duty cycle (v_{aero} and $\tilde{a}$) and another set only dependent on vehicle parameters. In so doing, we can clearly see the effect of duty cycle on energy use.

In equation 10, it is important to note that mass is assumed constant over each time step. If mass will change over the duty cycle, it may be easier to deal with equation 10 as "energy per distance." That is, equation 10 can be multiplied by vehicle mass if mass will vary over the cycle.

The coefficients presented in equation 10 are defined below:

Equation 11:

$$C_{aero} = \frac{\frac{1}{2}\cdot\rho\cdot C_D\cdot FA}{M_{veh}}$$

$$C_{rolling} = RRC_0\cdot g$$

$$v^2_{aero,j,j+1} = \frac{\overline{v^3_{j,j+1}}\cdot\Delta t_{j,j+1}}{\Delta D_{j,j+1}} = \frac{\overline{v^3_{j,j+1}}}{\overline{v_{j,j+1}}}$$

$$\tilde{a}_{j,j+1} = \frac{1}{2}\cdot\frac{(v^2_{j+1}-v^2_j)}{\Delta D_{j,j+1}} + g\cdot\frac{(h_{j+1}-h_j)}{\Delta D_{j,j+1}}$$

$$v_{aero} = \text{aerodynamic speed}$$

$$\tilde{a} = \text{characteristic acceleration}$$

Characteristic acceleration and aerodynamic speed can be determined for an entire duty cycle as follows:

Equation 12:

$$\tilde{a} = \frac{\sum_{j=1}^{N-1} positive(\frac{1}{2}\cdot(v^2_{j+1}-v^2_j)+g\cdot(h_{j+1}-h_j))}{D}$$

The aerodynamic speed for a duty cycle is defined as:

Equation 13:

$$v^2_{aero} = \frac{\frac{1}{T_{driving}}\int_0^T v^3 dt}{\frac{1}{T_{driving}}\int_0^T v dt} \cong \frac{\sum_{j=1}^{N-1}\overline{v^3_{j,j+1}}\cdot\Delta t_{j,j+1}}{\sum_{j=1}^{N-1}\overline{v_{j,j+1}}\cdot\Delta t_{j,j+1}} = \frac{\sum_{j=1}^{N-1}\overline{v^3_{j,j+1}}\cdot\Delta t_{j,j+1}}{D}$$

We will revisit the characteristic acceleration and aerodynamic speed in the next section, as they have usefulness over and above their ability to simplify the math of the roadload equation.

Let us now divide equation 6 by vehicle mass and duty cycle distance and insert equation 10. This results in the following relation for specific fuel consumption (SFC). SFC is fuel energy per unit mass of the vehicle per unit distance as defined in equation 14.

Equation 14:

$$SFC = \frac{SEPD_{road,pos} + SEPD_{road,neg}\cdot\overline{\eta_{regen}}}{\overline{\eta_{powertrain}}} + \frac{E_{fuel,other}}{M_{veh}\cdot D}$$

In equation 14, $SEPD_{road,pos}$ and $SEPD_{road,neg}$ are defined as follows:

Equation 15:

$$SEPD_{road,pos} = \sum_{j=1}^{N-1} positive(SEPD_{road,j,j+1})$$

$$SEPD_{road,neg} = \sum_{j=1}^{N-1} negative(SEPD_{road,j,j+1})$$

We can further simplify equation 14 by approximating the $SEPD_{road}$ positive and negative terms as follows:

Equation 16:

$$SFC \cong \frac{C_{aero}\cdot v^2_{aero} + C_{rolling} + \tilde{a}\cdot(1-\overline{\eta_{regen}})}{\overline{\eta_{powertrain}}} + \frac{E_{fuel,other}}{M_{veh}\cdot D}$$

Equation 16 is useful for investigating how aerodynamic speed and characteristic acceleration affect fuel consumption. However, for rigorous calculation of the specific fuel consumption, equation 14 should be used since equation 16 only approximates the time-step summation of roadload components. Equation 16 disregards the timing of roadload events.

CYCLE METRICS

In the previous section, we derived the roadload equation and discussed how it relates to heavy vehicle fuel consumption. Two cycle metrics were introduced: the characteristic acceleration (equation 12) and aerodynamic speed (equation 13). We will discuss the significance of these two metrics and derive two more in this section.

The characteristic acceleration measures the inertial work to accelerate and/or raise the vehicle per unit mass per unit distance over the cycle. It is the positive part of specific kinetic and potential energy per distance associated with moving a vehicle over a duty cycle. The characteristic acceleration reduces to the actual acceleration for a linear speed increase over constant grade. Characteristic acceleration is proportional by a constant factor to the term “PKE“ introduced by reference [2]. We have chosen to use characteristic acceleration over PKE to keep the direct physical link with the roadload equation.

The aerodynamic speed (or more accurately, the square of the aerodynamic speed) measures the ratio of the overall average cubic speed to the average speed. It is directly linked to the impact of aerodynamics on vehicle fuel usage. The aerodynamic speed for a constant speed cycle would be the constant speed of the cycle.

Perhaps the most important aspects of the characteristic acceleration and aerodynamic speed lie in the fact that they characterize the speed and elevation versus time of any given duty cycle for cycle energy usage. Thus, these are useful parameters to use when comparing one duty cycle to another for similarity.

Let us now link the cycle metrics to hybrid vehicles by introducing the concept of "hybrid advantage." Hybrid advantage is the percent reduction in fuel consumption of a hybrid electric vehicle over a conventional vehicle.

Equation 17:

$$HA = \frac{E_{fuel,CV} - E_{fuel,HEV}}{E_{fuel,CV}} \cdot 100\% \text{ and}$$
$$= \left(1 - \frac{SFC_{HEV}}{SFC_{CV}}\right) \cdot 100\% \; iff \; M_{veh} \text{ is constant}$$

Let us for the moment neglect non-tractive effort fuel consumption (i.e., E_{other} = 0) and assume a conventional vehicle (CV) and hybrid vehicle (HEV) where the only difference between the two is the powertrain (i.e., vehicle mass, drag coefficient, powertrain efficiency, rolling resistance, etc. are the same). If we substitute equation 16 into equation 17 under these assumptions, we get the following:

Equation 18:

$$HA \cong 1 - \frac{C_{aero} \cdot v_{aero}^2 + C_{rolling} + \tilde{a} \cdot (1 - \overline{\eta_{regen}})}{C_{aero} \cdot v_{aero}^2 + C_{rolling} + \tilde{a}}$$
$$= \frac{\eta_{regen}}{C_{aero} \cdot \frac{v_{aero}{}^2}{\tilde{a}} + \frac{C_{rolling}}{\tilde{a}} + 1}$$

We'd like to draw the reader's attention to the square of aerodynamic speed over the characteristic acceleration which appears in the denominator of equation 18. Note that if we could neglect rolling resistance, the only duty cycle specific term left in equation 18 is this ratio. Because the ratio appears in the denominator, let us introduce a new cycle metric, kinetic intensity, which is one over the combination of the two metrics seen in equation 18.

Kinetic intensity relates well to a hybrid electric vehicle's hybrid advantage for cases where idle fuel usage and vocational loads are small compared with the fuel usage to satisfy roadload. As the ratio of characteristic acceleration to aerodynamic speed increases, we see from equation 18 that the hybrid advantage will also increase.

Equation 19:

$$ki = \frac{\tilde{a}}{v_{aero}^2}$$
$$\cong \frac{\sum_{j=1}^{N-1} positive(\frac{1}{2} \cdot (v_{j+1}^2 - v_j^2) + g \cdot (h_{j+1} - h_j))}{\sum_{j=1}^{N-1} \overline{v_{j,j+1}^3} \cdot \Delta t_{j,j+1}}$$

What about the case when idle and vocational load fuel consumption cannot be neglected?

To simplify things, let's first introduce our final metric, β, that is the ratio of "other" fuel consumption to the positive tractive effort required over a cycle:

Equation 20:

$$\beta = \frac{\frac{E_{fuel,other}}{M_{veh} \cdot D}}{SEPD_{road,pos}} = \frac{E_{fuel,other}}{E_{road,pos}} \cong \frac{\frac{E_{fuel,other}}{M_{veh} \cdot D}}{C_{aero} \cdot v_{aero}^2 + C_{rolling} + \tilde{a}}$$

Note that this definition of β ratios fuel energy (e.g., diesel fuel) for non-propulsion efforts to energy at the road-wheel interface to move the vehicle (e.g., integrated wheel torque and angular speed). Care must be taken in interpreting the β parameter because it is a ratio of diesel fuel energy to wheel work energy (i.e., disparate units). This was done to ease calculation of the β parameter. If a target vehicle exists, then fuel consumption can be measured with and without non-propulsion loads over a fixed cycle. The difference in the two fuel consumptions would yield the numerator. The denominator can be mathematically calculated from the cycle and base vehicle characteristics as per equation 7. If we wanted to rephrase the β term as the percent fuel consumption of non-propulsion loads versus total fuel consumption, we would need to adjust the denominator of the β term using the average powertrain efficiency. For example, if the average powertrain efficiency is 25%, a β value of 1 would correspond to [1/(1/0.25+1)] x 100% or 20% of fuel usage going to non-propulsion efforts (a ratio of the fuel to non-propulsion loads to the fuel to both propulsion and non-propulsion loads).

Now let's revisit equation 18, this time without neglecting the $E_{fuel,other}$ term from equation 16. We will assume $E_{fuel,other}$ is the same for both conventional vehicle and hybrid. We will also continue to assume the cycle average powertrain efficiency is the same for both vehicles. With these assumptions, we have:

Substituting the definition of β into equation 18 without neglecting $E_{fuel,other}$ yields:

Equation 21:

$$HA \cong \left(\frac{\overline{\eta_{regen}}}{C_{aero} \cdot \frac{v_{aero}^2}{\tilde{a}} + \frac{C_{rolling}}{\tilde{a}} + 1} \right) \cdot \left(\frac{1}{1 + \beta \cdot \overline{\eta_{powertrain}}} \right)$$

As β grows larger, the hybrid advantage decreases. Although β is not strictly a duty-cycle metric (it contains the vehicle specific $E_{fuel,other}$ term), it relates duty-cycle energy consumption to other energy consumption mechanisms aboard the vehicle. This is a critical parameter to check as we shall see.

APPLICATIONS FOR CYCLE METRICS

In the previous sections, we have reviewed the energy equation for roadload, proposed a simple model of how duty cycle relates to vehicle fuel consumption, and have introduced four duty cycle metrics. This section will discuss some of the ways the metrics can be applied to characterize duty cycles and evaluate the applicability of hybridization for an application.

Characterizing and Comparing Duty Cycles

As mentioned previously, the characteristic acceleration and aerodynamic speed metrics can be used to quantitatively characterize and compare duty cycles on an energy basis. This is because both metrics completely represent the duty cycle impact on the roadload equation (within the bounds of the assumptions made for equation 2). If the assumptions for equation 6 also hold true and the non-tractive effort fuel usage per distance is either small or constant over cycles, characteristic acceleration and aerodynamic speed are good characteristic metrics for comparisons on a fuel energy basis as well.

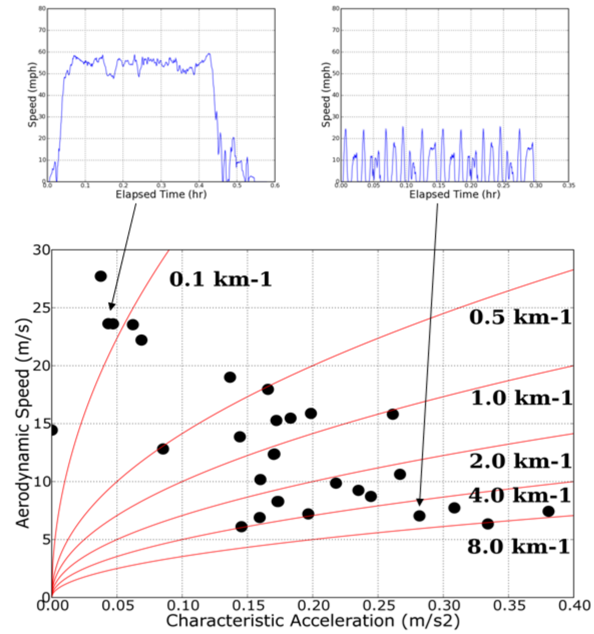

Figure 1: Heavy Vehicle Cycle Characterization

Several publicly available heavy vehicle duty cycles are plotted in Figure 1 by the cycle characteristic acceleration and aerodynamic speed. The kinetic intensity is overlaid as lines on the figure. Due to the nature of heavy truck duty cycles, we tend to see cycles with high aerodynamic speed and low characteristic acceleration or cycles with higher characteristic acceleration and low aerodynamic speed.

Each data point in Figure 1 shows the representative cycle characteristic acceleration and aerodynamic speed for an entire cycle. Two example cycles are shown to give the reader a flavor of the trace belonging to the given characteristics. The high-speed cycle on the top left is the cruise3 cycle [5] and the low speed cycle on the top right is the Manhattan cycle [6]. Because these macro values relate directly to equation 10, they are the correct numbers to use for energy use estimation. However, to get a sense of the range and scatter of the microtrips within a cycle (a microtrip is the segment of a time-speed trace from a start to a subsequent stop) within a single duty cycle, we can recreate Figure 1 with one point per microtrip. This appears in Figure 2.

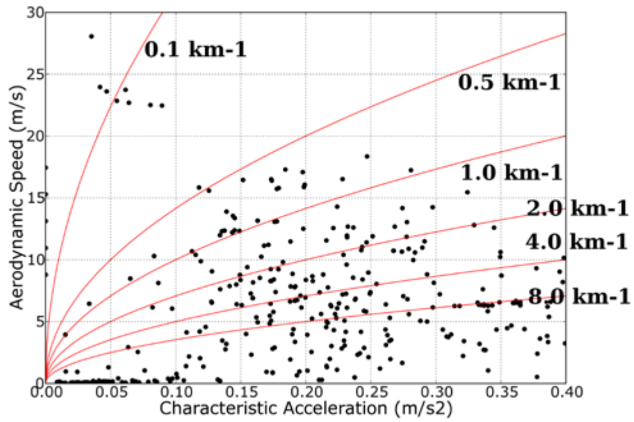

Figure 2: Heavy Vehicle Cycle Microtrips

The kinetic intensity helps us to differentiate between cycles that might be good for hybridization and others that might not be so good. Said another way, a general rule of thumb would be that cycles with relatively high characteristic acceleration versus aerodynamic speed are good for hybridization. However, this does not always mean that a cycle with low kinetic intensity should never be used for hybrids as there are some caveats related to the use of vocational loads (accessories).

For example, some hybrids have features for auto-engine shut-off to disable fuel usage when the vehicle is stopped and not utilizing significant vocational loads. These benefits would not show up in the kinetic intensity factor, but would be evident from the β metric. However, in as much as the duty cycle emphasizes tractive effort (i.e., moving the vehicle), the benefits a hybrid can gain from regenerative braking appear well represented by the kinetic intensity.

Estimating Fuel Consumption for a Target Application

Let us consider the specific fuel consumption as modeled by equation 14. This equation is very handy should we wish to estimate the fuel economy benefit of a hybrid over some target application in the absence of more concrete data.

From equation 14, if we know the target application duty cycle (at least the speed and optionally elevation versus time) and we know some basics about the target vehicle (frontal area, coefficient of drag, rolling resistance, etc.), we can parametrically sweep the fuel usage for various vocational load scenarios (the $E_{fuel,other}$ term). Equation 16 should not be used as it will introduce significant errors into the estimate. A spreadsheet can be used to implement equation 14. To put things into units of energy per distance, we will multiply equation 14 by the vehicle mass.

To demonstrate the parametric form of equation 14, let us consider a transit bus with the specifications as given in Table 2.

Table 2: Hypothetical Transit Bus

Parameter	**Value**
tested mass (kg)	14,515
coefficient of drag	0.8
frontal area (m2)	8.0
rolling resistance	0.01
accessory power	31 kW

Let's examine the vehicle from Table 2 over the Orange County Cycle [6]. Metrics for this cycle are given in Table 3.

Table 3: Statistics for the Orange County Cycle (OCTA)

Parameter	**Value**
characteristic acceleration (m/s2)	0.218
aerodynamic speed (m/s)	9.88
kinetic intensity (km^{-1})	2.23
total distance (km)	10.53
average speed (m/s)	5.51
elapsed time (s)	1909

Using the metrics and parameters from Tables 2 and 3, we can sweep the cycle averaged powertrain and cycle averaged regen capture and redeploy efficiencies. This yields a response surface of fuel consumption by the cycle averaged efficiencies. Example surface plots for our hypothetical transit bus are shown in Figures 3 and 4.

The most difficult part of using equation 14 is determining proper values of the powertrain efficiency, regenerative braking round-trip efficiency, and fuel use for vocational loads. However, the benefit of this technique is not so much in the accurate prediction of a single fuel economy but in the quick estimation of possible fuel economies. For example, in Figure 4 we can quickly determine that the maximum potential benefit from a hybrid might be around 3.5 mpg at best, based on theoretical limits to regen and powertrain efficiencies as shown via the shaded region of Figure 4.

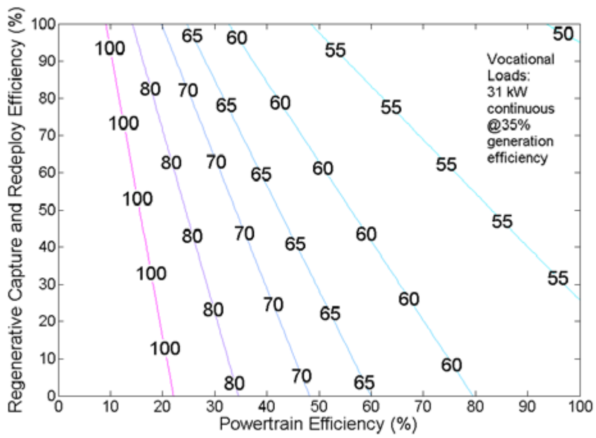

Figure 3: Fuel Consumption Response to Efficiency over OCTA

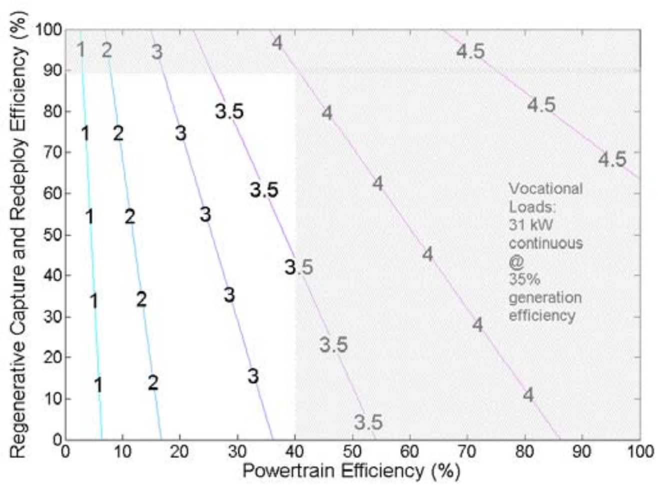

Figure 4: Fuel Economy Response to Efficiency over OCTA

The Effect of Vocational Loads on Hybrid Advantage

As noted from equation 21, the higher the non-tractive energy input to tractive energy input (i.e., the higher the β value), the lower a vehicle's hybrid advantage will be. Equation 21 assumes that a hybrid and baseline conventional vehicle will have the same non-tractive specific fuel consumption values (i.e., $E_{fuel,other}$). This is not necessarily the case, depending upon the hybrid vehicle technology involved. If the hybrid does indeed have differing non-tractive loads as compared to the conventional vehicle, then equation 21 must be re-derived with a separate β value for each vehicle.

For our purposes here, we will consider the case where a hybrid and conventional vehicle have similar non-tractive fuel consumptions (i.e., $E_{fuel,other}$) and examine how this fuel usage affects hybrid advantage.

Figure 4 shows the hybrid advantage for the hypothetical transit bus given in Table 2 as a function of β. Different regen braking efficiencies are assumed with a constant cycle averaged powertrain efficiency of 30%.

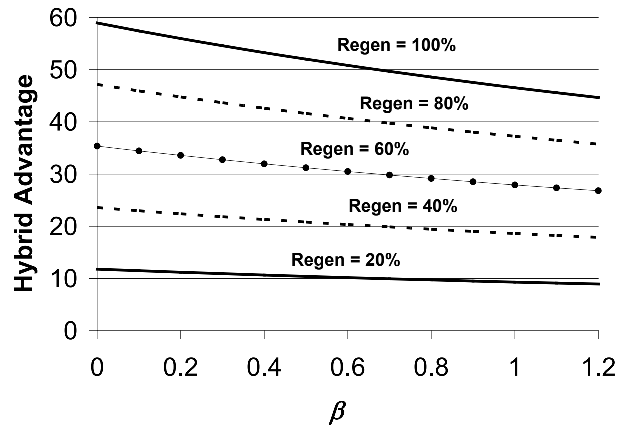

Figure 4: The Effect of β on Hybrid Advantage

Referring to Figure 4, we see that hybrid advantage diminishes as β increases. The assumptions behind Figure 4 are that both the hybrid and baseline have the same powertrain efficiency and vehicle weight. The regenerative braking roundtrip efficiency (the percentage of available regen braking energy that is captured and redeployed to offset tractive effort) is swept from 20% to 100%. The β parameter's influence increases as regenerative braking efficiency increases.

TEST DATA AND REAL-WORLD APPLICATIONS

In this section, we provide data that support the relationships between duty cycle and fuel consumption identified earlier in this paper. Additionally, we present some real-world applications of the cycle characterization methodology.

Kinetic Intensity vs. Hybrid Advantage

Here we present data for a series/parallel hybrid electric 60' articulated transit bus that was tested at the National Renewable Energy Laboratory's (NREL's) ReFUEL heavy vehicle chassis dynamometer facility in Denver, Colorado, USA. The hybrid transit bus data is compared to a conventional 60' articulated transit bus of comparable performance. For an in-depth background on this dataset, see reference [7].

The hybrid and conventional vehicles were tested over four different test cycles: the central business district cycle (CBD-14) [6], the King County Cycle with and without grade information (KINGCO and KINGNG respectively—created at NREL from GPS data obtained in Seattle, Washington USA) [7], the Orange County Cycle [6], and the Manhattan Cycle [6].

The kinetic intensity of each of these cycles can be calculated using equation 19. A plot of hybrid advantage measured directly from test data versus kinetic intensity appears in Figure 5. Recall that hybrid advantage is defined in this paper as the percent reduction in fuel consumption of the hybrid as compared to the baseline conventional vehicle. Note that the curve obtained from Figure 5 is specific to the baseline and hybrid vehicles being compared. Although we don't have enough data to validate the relationship between kinetic intensity and hybrid advantage conclusively, we propose that the kinetic intensity metric can be used to predict how the vehicle's hybrid advantage might change over an as-yet untested cycle.

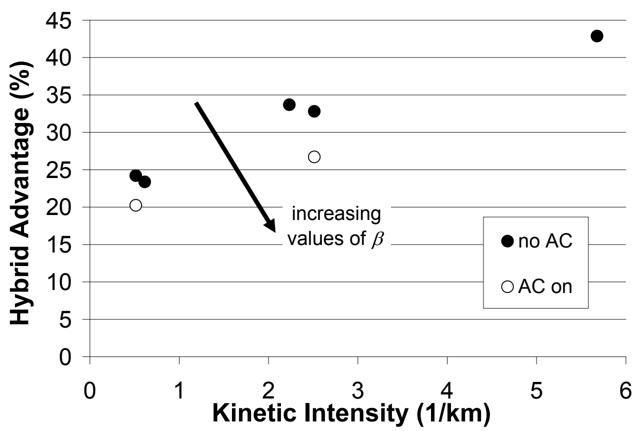

Figure 5: Hybrid Advantage vs. Kinetic Intensity

In Figure 5, the kinetic intensity of the cycle is determined using the desired cycle trace as opposed to the actual speed time trace created by the driver. Thus, driver variation is not shown on the graph. The value of β for the AC-on scenarios is estimated at 0.4 over the King County Cycle and 0.9 over the CBD-14 cycle based on the estimated $E_{road,pos}$ values for a vehicle of the given size over the given duty cycle and the measured differences in fuel consumption between AC-on and AC-off runs.

Analyzing a Detailed GPS Dataset Using Metrics

As one of several projects under the Department of Energy's (DOE) Advanced Heavy Hybrid Program, Oshkosh Truck Corporation, Ohio State University (OSU), and NREL worked together to develop drive and load cycles relative to various operations of refuse trucks in various geographical locations. A single refuse truck was instrumented and data were collected and processed by OSU for six major U.S. cities. The truck was a 2003 Autocar WXR64 Chassis with Cummins ISM 320 HP Engine and Allison HD4560 5-speed transmission. The vehicle ran with a McNeilus body configured as a residential automated side-loader (ASL). The vehicle's empty weight was 34,100 lbs with a legal payload capability of 16,000 lbs. Refer to reference [8] for more background on this project.

An example of the data collected through this effort appears in Figure 6. From top to bottom, we can see variations in vehicle speed, side-arm hydraulic power, packing hydraulic power, and finally vehicle weight versus time.

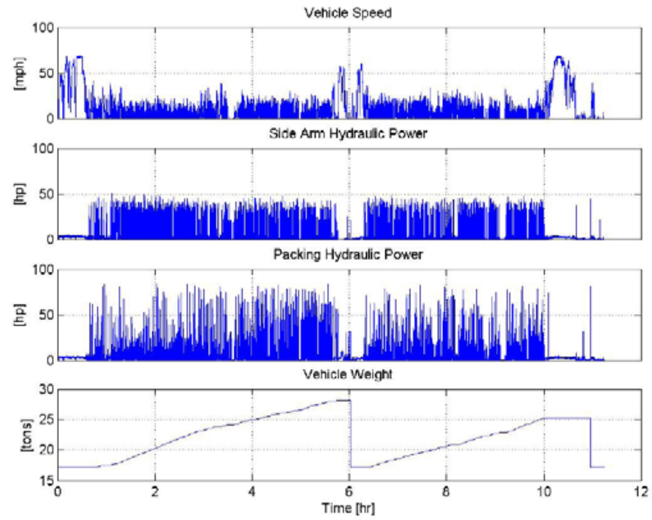

Figure 6: Refuse Hauler Data Collection Sample

Zooming in on a segment in Figure 7, we see that the refuse hauler always seems to be working and thus it is hard to characterize the vehicle as ever being "at idle."

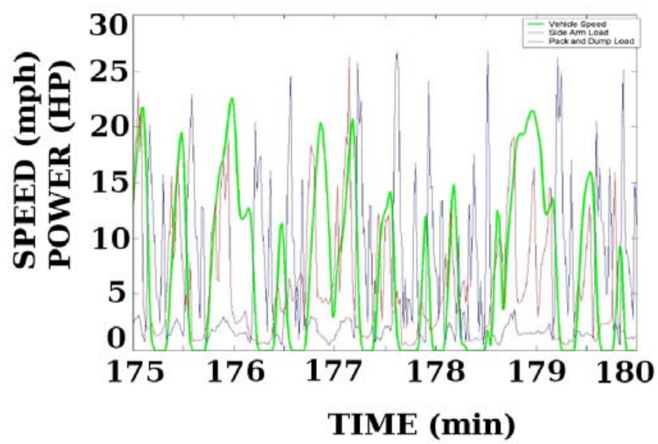

Figure 7: A Close-up of Vehicle Loads

The datasets collected from the six cities were used by Ohio State University (OSU) to synthesize five representative cycles that could be used for dynamometer testing. The technique employed was an advanced statistical clustering technique as detailed in reference [8].

In the remainder of this section, we will use the cycle metrics derived in this paper to show how the five synthesized cycles created by OSU compare with the overall dataset from testing over the six cities and with other publicly available refuse hauler cycles. The five cycles characterize specific segments of the automated side-loader refuse operation: approach to the residential pickup zone from the dumpsite (unloaded), return to the dumpsite from the residential pickup zone (fully loaded), and three variations to characterize the types of trips encountered in the residential pick-up zone (routes 1, 2, and 3). These routes are shown in Figure 8 along with an overall composite score that reflects the approach and return trips placed together with appropriate distance weightings (the triangular marker in Figure 8).

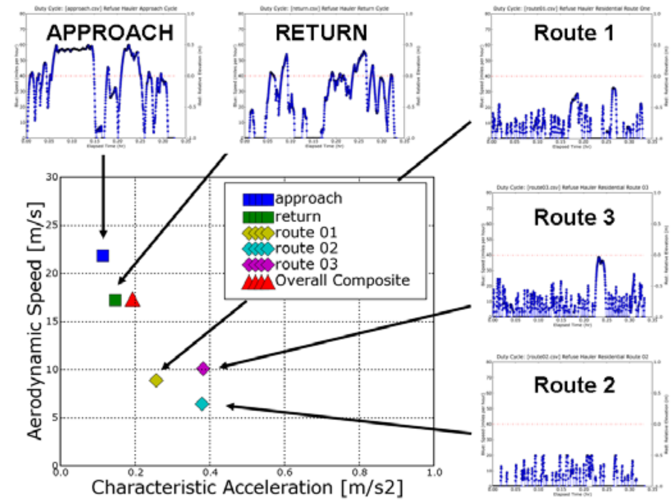

Figure 8: Characterization of the Five OSU Synthetic Cycles

Note from Figure 8 that the overall composite characteristic acceleration/aerodynamic speed score is quite close to the high-speed approach and return cycles. This is a subtlety that deserves to be pointed out to the reader. Recall that the equations for characteristic acceleration and aerodynamic speed (equations 12 and 13) are distance based. Thus, it should be of no surprise that the long-distance approach and return segments dominate the time-speed-elevation aspect of the moving part of the refuse hauler duty cycle. However, this is not the whole story.

As one might suspect from examining Figure 7, the refuse hauler vocation is a vocation characterized by a high β value. That is, non-motive fuel usage can be quite high as compared to the required road-load. Hybrid systems that attack both the non-motive fuel usage as well as capitalize on regenerative braking from the route sections (well-suited to hybridization) should do well.

As a final exercise, let us compare the OSU synthesized cycles with the dataset as a whole. Figure 9 is a plot from each day of testing in the six cities. The time-speed-elevation portion of the cycle data is characterized in Figure 9 by aerodynamic speed and characteristic acceleration. The cycle data from each day of testing are separated by high-speed segments (light colored markers on the top left), residential pick-up segments (light colored markers on the bottom right), and by overall characteristics (the black markers towards the center of the graph). Note how well the OSU synthesized cycles presented in Figure 8 agree with the city data of Figure 9. For example, the three route segments with characteristic acceleration between 0.25 and 0.40 m/s^2 and aerodynamic speeds between 6 and 11 nicely bound the residential pick-up portion of the tested daily trips. Similarly, the overall composite characteristic acceleration and aerodynamic speed of the OSU synthesized cycles (approximately 17 m/s and 0.2 m/s^2 respectively) lie well within the overall composite scatter of the daily city testing in Figure 9.

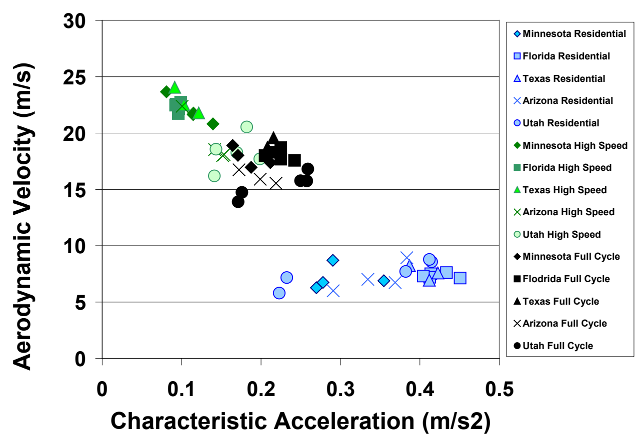

Figure 9: Automated Side Loader Collection Data Summary

CONCLUSION

This paper introduces four duty-cycle based metrics derived from the classic vehicle roadload equation and a simple model of vehicle fuel consumption. The metrics include characteristic acceleration, aerodynamic speed, kinetic intensity, and β, a metric to relate non-propulsion fuel use to fuel used for tractive effort.

Because the metrics are derived from the roadload equation, they have a physical connection to energy usage. Except for the β metric, all metrics are exclusively related to duty cycle and thus can be used to characterize, compare, and evaluate the hybrid applicability of duty cycles *independent of the vehicle* being considered.

Three specific applications for the metrics are given:

1. Using the metrics to quantitatively compare/contrast duty cycles and microtrips from an energy standpoint for their similarity and applicability for hybrid vehicle usage.
2. Using the metrics and the concepts of cycle averaged efficiency to estimate the fuel consumption of a vehicle over a target application.
3. Using the β metric to check predictions and comparisons of hybrid advantage based on how non-propulsion fuel consumption compares to fuel for tractive effort.

Two real-world use-cases for the metrics are given to show how the principles discussed here can be applied to real examples. The first case shows how the kinetic intensity relates to the hybrid advantage of a hybrid transit bus compared to its conventional counterpart for dynamometer testing over several duty cycles.

The second case shows how a large detailed dataset obtained from an instrumented refuse hauler can be characterized using the metrics from this paper.

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CONTACT

Michael O'Keefe is a senior research engineer working with the Center for Transportation Technologies and Systems at the National Renewable Energy Laboratory. Michael's area of emphasis is in the simulation of heavy vehicle powertrains and thermal systems. Michael may be contacted at michael_okeefe@nrel.gov for questions pertaining to this research.

Andrew Simpson, formerly with the National Renewable Energy Laboratory, is now a key platform engineer with Tesla Motors in California, manufacturers of high performance electric vehicles. Andrew's PhD thesis work, conducted at the University of Queensland in Australia, forms the basis of the work presented here.

Dan Pedersen is a leading member of Oshkosh Truck Corporation's advanced products group which is focused on the design and development of advanced hybrid electric vehicles.

Ken Kelly is a senior research engineer at the National Renewable Energy Laboratory and leads the Thermal Controls portion of the Advanced Power Electronics and Electric Machines program.

DEFINITIONS

ρ: air density (mass per volume)

C_D: coefficient of drag

M_{veh}: mass of the vehicle

RRC_0: zeroth rolling resistance coefficient as the dimensionless ratio of force resisting rolling divided by force due to vehicle mass

HA: **hybrid advantage**: percent reduction in fuel consumption of a hybrid over a comparable conventional vehicle $(FUEL_{CONV} - FUEL_{HEV}) \bullet 100\%/FUEL_{CONV}$

$\tilde{a}$: **characteristic acceleration**: a measure of a cycle's acceleration and grade intensity

v_{aero}: **aerodynamic speed**: the ratio of the average cubic speed to the average speed of a cycle

ki: **kinetic intensity**: ratio of characteristic acceleration to the square of aerodynamic speed

β: ratio of the fuel used for non-propulsion to the roadload for a vehicle over a given cycle

P_{road}: the power required to overcome vehicle roadload

FA: frontal area for aerodynamic considerations

v: vehicle speed

g: acceleration due to gravity

t: time

h: height above some fixed reference

j: sample time counter. the subscript $j,j+1$ refers to the time step from sample time j to sample time $j+1$ where $t_{j+1} > t_j$

E: energy usage. E_{fuel} is a fuel usage. E_{road} is roadload energy. $E_{supplemental}$ is energy supplementing engine shaft energy from an energy storage system. E_{charge} is the energy to recharge an HEV energy storage system. $E_{fuel,voc}$ is the fuel used to power vocational loads. $E_{fuel,idle}$ is the fuel used when the vehicle is performing no useful work (i.e., no power to tractive effort or vocational loads). $E_{fuel,other}$ is the fuel used for other than vehicle tractive effort.

η: efficiency. $\eta_{powertrain}$ (with an overbar) is approximately the cycle average efficiency of transforming fuel energy to required roadload. η_{regen} (with an overbar) is cycle averaged roundtrip regen efficiency required to capture available regenerative braking energy from absorbed roadload energy and redeploy that energy to required tractive effort.

SEPD: specific energy per distance (energy per unit mass per unit distance)

SFC: specific fuel consumption (fuel energy per unit mass per unit distance)