**TRB-14-1220**

# DEVELOPMENT OF A SHORT-DURATION DRIVE CYCLE TO REPRESENT LONG-TERM MEASURED DRIVE CYCLE DATA FOR THE EVALUATION OF TRUCK EFFICIENCY TECHNOLOGIES IN CLASS 8 TRACTOR-TRAILERS

July 29, 2013
Word Count: 8084 (including 8 figures and 3 tables)

**Tim J. LaClair (Corresponding Author)**
Oak Ridge National Laboratory
National Transportation Research Center
2360 Cherahala Boulevard
Knoxville, TN 37932, USA
Tel.: +1-865-946-1305; Fax: + 1-865-946-1541
E-mail: laclairtj@ornl.gov

**Zhiming Gao**
Oak Ridge National Laboratory
National Transportation Research Center
2360 Cherahala Boulevard
Knoxville, TN 37932, USA
Tel.: +1-865-946-1339; Fax: + 1-865-946-1354
E-mail: gaoz@ornl.gov

**Joshua S. Fu**
The University of Tennessee
Department of Civil & Environmental Engineering
Knoxville, TN 37996-2010
Tel.: +1- 865-974-2629; Fax: + 1- 865-974-2669
E-mail: jsfu@utk.edu

**Jimmy Calcagno**
The University of Tennessee
Department of Civil & Environmental Engineering
Knoxville, TN 37996-2010
Tel.: +1- 865-974-7723
E-mail: jacal@utk.edu

**Jeongran Yun**
The University of Tennessee
Department of Civil & Environmental Engineering
Knoxville, TN 37996-2010
E-mail: jyun@utk.edu

Paper submitted for peer review for the 93rd Transportation Research Board Annual Meeting.
Submission Date: November 15, 2013

## ABSTRACT

Quantifying the fuel savings and emissions reductions that can be achieved from different truck fuel efficiency technologies for a fleet's specific usage allows the fleet to select a combination of technologies that will yield the greatest operational efficiency and profitability. An accurate characterization of usage for the fleet, however, is critical for such an evaluation, but short-term measured drive cycle data do not generally reflect overall usage very effectively. This paper presents a detailed analysis of vehicle usage in a commercial vehicle fleet and demonstrates the development of a short duration synthetic drive cycle using measured drive cycle data collected over an extended period of time. An approach is used that matches statistical measures of the vehicle speed and acceleration history, and integrates measured grade data, to develop a compressed drive cycle that accurately represents the total usage. Drive cycle measurements obtained during a period of a full year from six tractor-trailers in normal operations in a less-than-truckload (LTL) carrier were analyzed to develop a synthetic drive cycle. The vehicle mass was also estimated to account for the variation of loads that the fleet experienced. These drive cycle and mass data were analyzed using a tractive energy analysis to quantify the fuel efficiency and CO2 emissions benefits that can be achieved on class 8 tractor-trailers when using advanced efficiency technologies, either individually or in combination. Although differences exist among class 8 tractor-trailer fleets, this study provides valuable insight into the energy and emissions reduction potential that various technologies can bring in this important trucking application. The methodology employed for generating the synthetic drive cycle serves as a rigorous approach to develop an accurate usage characterization that can be used to effectively compress large quantities of drive cycle data.

## INTRODUCTION

Medium- and heavy-duty trucks and buses are responsible for over 26% of the energy used and emissions generated in highway transportation, and class 8 tractor-trailers operating in long-haul and regional cargo transport are responsible for about 75% of all fuel consumed by commercial trucks [1]. The vehicle miles traveled (VMT) for trucks is expected to increase at a rate significantly outpacing passenger VMT growth, which will result in a steady rise in the percentage of energy consumption (and emissions) attributable to trucks over the coming decades. These facts have sparked significant recent interest in truck fuel efficiency in the transportation community.

Although fuel economy regulations in the United States have historically focused on passenger cars, new standards for fuel economy in medium- and heavy-duty trucks [2] aim to increase the efficiency of trucks as well. The development of regulations for truck fuel efficiency is quite challenging, however, since vehicle usage and configurations vary substantially among the very diverse set of trucking applications. Fleets that wish to evaluate how to achieve the greatest fuel savings face similar difficulties in quantifying the benefits of any given technology. Fuel economy is very strongly linked to the particular drive cycle followed by a given truck, as are the gains in efficiency that can be realized by implementing new technologies. A technology that provides significant fuel efficiency gains for one trucking application may yield little improvement or could even be detrimental to fuel economy in a different trucking application. It is therefore critical that the usage of each application be well understood and carefully evaluated to select the set of technologies that can provide the greatest benefits for each application. This paper focuses on a methodology for characterizing vehicle usage based on measured drive cycle data, and a highly representative drive cycle for a class 8 tractor-trailer application is developed.

Although it is well known that drive cycle data representative of a vehicle or fleet's usage is crucial for an accurate evaluation of fuel economy [3-5] or to identify an optimum set of technologies to reduce fuel consumption, detailed drive cycle data measured over extended periods of time and with multiple vehicles in a fleet are not broadly available to researchers. The Oak Ridge National Laboratory (ORNL) has collected a relatively significant set of truck duty cycle data in an effort to characterize the usage of several trucking applications [6,7]. During the first phase of ORNL's duty cycle data collection activities, drive cycle measurements were made from six class 8 tractor-trailers during normal operations in a regional commercial shipping fleet, operating primarily in the southeastern U.S., for a period of a full year. This data, contained in the Heavy Truck Duty Cycle (HTDC) project database, was analyzed in detail for the current research effort. The HTDC measurements include (among other channels) the following data: (1) standard outputs from the vehicle J1939 data bus, including vehicle speed, engine speed, engine torque, and fuel consumption rate; (2) GPS measurement of location, elevation and speed; and (3) axle weight measurements based on the pressure contained in the air bags of the suspension system. Further details of the measured data are provided in reference [6].

The end objective of this research is to use the representative drive cycle data to quantify the potential fuel consumption reductions that can be achieved using advanced energy efficiency technologies for a class 8 trucking operation, including combinations of these technologies. To evaluate the potential fuel savings and CO2 emissions reductions from these technologies, a novel analysis approach was followed. First, a synthetic drive cycle that is highly representative of the complete operation of the fleet was developed, based on a statistical analysis of the entire set of drive cycle measurements collected during ORNL's previous study. The synthetic drive cycle is appropriate to use both for modeling and testing purposes, and the results when using this cycle should very closely match the overall performance for the trucking fleet since the drive cycle measurements were collected from six trucks during a full year of normal operations in the fleet. To evaluate the fuel savings that can be achieved with various energy efficiency technologies, a tractive energy analysis was employed using the synthetic drive cycles developed. The tractive energy is very convenient since its calculation requires only the drive cycle (speed and road grade (which was derived from the measured elevation data) as a function of time), along with a limited set of parameters characterizing the energy losses associated with propulsion of the vehicle, and it correlates extremely well with the vehicle fuel consumption during powered driving [8]. An additional result of the analysis of the drive cycle data included a determination of the mass distribution of the vehicles during the fleet's operations, and this distribution was also incorporated in the analysis for assessing the fuel savings potential for the fleet. The final result of this study is an assessment of the overall potential for fuel savings reduction that can be expected if any combination of the technologies considered were to be implemented in the fleet.

## GENERATION OF A SYNTHETIC DRIVE CYCLE FROM MEASURED FLEET USAGE DATA

The development of a synthetic drive cycle using long-term fleet measurements is a new approach for generating a drive cycle that is intended to be highly representative of the overall operations. Due to the manner in which the synthetic drive cycle is generated, the results from an analysis or test when using it will be extremely similar to those that would be achieved if the complete data set were analyzed or tested. Therefore, when a large data set representative of the fleet operations is used as the basis for developing the synthetic drive cycle, the cycle can be used to estimate, with high accuracy, the fuel savings benefits attainable in the fleet if particular technologies are deployed. It is noted that this method is appropriate for fleets with relatively uniform operations, so that the drive cycle is similar for the various vehicles in the fleet. If there are many types of vehicles or very different routes are followed by some vehicles in the fleet, then it may be more necessary to complete a separate analysis for the different vehicle groups within the fleet. Other complications in drive cycle and mass variations may make this approach challenging to apply for specific applications. For example, the nearly continuous increase in mass throughout the course of a day for a residential garbage collection application may result in variations in drive cycle that cannot be addressed with the method presented in this paper. Further research is needed to determine how such mass variations might influence the drive cycle, and whether an approach can be developed to account for both the mass and speed changes in a manner that is consistent with the assumptions of the analysis.

### Data Pre-Processing

A total of 1711 files from the HTDC database, each representing one day of driving on an individual truck, were processed prior to using the data for creation of the synthetic drive cycles. The raw data were available in text files with each channel stored in a separate column and each row of data representing a separate 0.2-s time interval. The measured channels that were included for performing the present analysis include the time, engine torque, elevation, engine speed, and vehicle speed. The engine speed and torque data were included to allow the measured power to be determined, which was necessary for calculating the vehicle mass, as described in the next section.

A sequence of Visual Basic for Applications (VBA) programs were written and run in the Excel environment to perform the file processing, and the files were cleaned and verified in a multi-step process while performing several quality checks of the data. Approximately 1000 lines of VB code were written to perform all of the data processing, filtering and verification functions. Files for which potential errors or corrupt data were identified were reviewed manually to determine what data could be recovered, and data that was clearly corrupt was removed. Fortunately, the overall quality of the data was good, and it is estimated that less than 3% of all of the raw data from the HTDC data set required removal or cleaning.

Filtering was performed for both the speed and elevation data. A discrete first-order low-pass filter applied to a moving median of the raw speed signal was used prior to resampling the data at 1 Hz. Since measured GPS elevation data is known to be less accurate than horizontal positioning measurements (latitude and longitude) [10], the accuracy of the elevation measurements was an initial concern for being able to accurately quantify the tractive power requirements from the drive cycle data. Although recent research has focused on new approaches that can minimize errors associated with grade measurements using GPS [11,12], the collected data did not apply advanced techniques, and a solution for processing the available data was therefore needed to yield the highest quality grade data possible. The raw data for the GPS elevation was found to exhibit random jumps of up to a meter at any given time, and smaller variations over time in the GPS signal can cause the elevation data to drift somewhat, even when the vehicle is not in motion. These shifts in elevation result in large errors for the grade, which lead to rather significant discrepancies between the estimated and measured engine power. Fortunately, roadway elevation does not change rapidly and is very smooth with respect to distance traveled. Engineering standards for road design [13] provide guidelines for how rapidly roadway grade should change, and the maximum grade is also limited based on the type of road traveled. This smoothness of road grade allows the time-based GPS elevation signal to be effectively filtered by smoothing the measured changes in elevation that occur as a function of distance traveled. A filtering approach was developed that was found to provide very good *qualitative* comparisons with elevation of the surrounding landscape, based on U.S. Geologic Survey data. It should be noted, however, that USGS data is not highly representative of the localized grades since bridges, blasting and other regrading measures used during road construction lead to very different grades for highways than those of the surrounding landscape in mountainous terrain. The ability of the grade filtering to remove unrealistic grade excursions and provide smoothing at a level consistent with actual grade variations is apparent in Fig. 1. The grade data extracted from the GPS data represents a known weakness in the present analysis, and future studies should seek to use alternative techniques that ensure more accurate grade measurements.

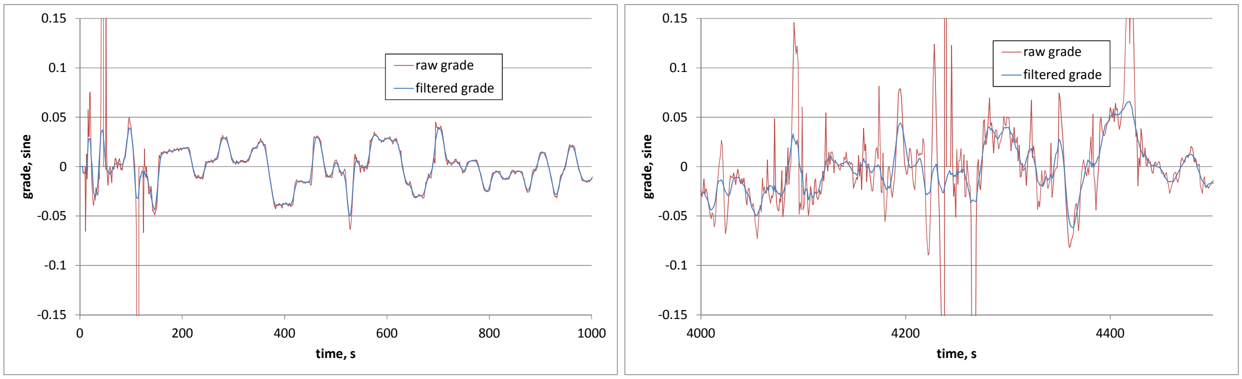

**FIGURE 1 Comparison of the grade determined from raw elevation data and after filtering, for two time segments.**

## Mass Estimations

The load carried by the vehicle is also important for the drive cycle characterization and this data is needed for each "micro-trip" in the drive cycle, i.e. each segment of driving between stops. In developing the synthetic drive cycle, it was decided that separate evaluations should be performed for different ranges of the total vehicle mass so that large differences in acceleration capabilities would not be mixed. Additionally, since the mass plays a primary role in the level of tractive power that is calculated, separating the data based on several ranges of the mass allows more accurate evaluation of the complete range of tractive power variations that occur for the vehicles during actual use.

By using the engine torque data, knowledge of the vehicle speed allows, in principle, a calculation of the mass based on Newton's second law of motion if all of the forces acting on the vehicle are known. Aerodynamic drag force, rolling resistance, and gravitational force can all be estimated using basic assumptions and the measured data. However, even small errors in the measured speed data can lead to large errors for instantaneous calculations of the acceleration, and the mass prediction done in this manner does not lead to consistent results during the driving segment. Averaging of the mass based on this approach is problematic, at least for an automated approach. If the measured engine power data (calculated from measured engine speed and torque) is used to estimate the tractive energy using a reasonable assumption for power transmission losses and an average power required from the vehicle accessories, then the measured tractive energy over the drive segment (based on the measured engine power output) can be compared to the cumulative tractive energy that is calculated using only the drive cycle data (along with the relevant vehicle parameters). By iteratively adjusting the mass value in the speed-based tractive energy calculation, one can determine the appropriate mass so that the two tractive energy values are matched. This approach integrates the instantaneous values of forces and accelerations so that the data are automatically smoothed and averaged using a physically based metric—the tractive energy—that relates directly to the vehicle mass.

The mass remains nearly constant during any period of continuous driving, since the only mass change is the fuel consumed during travel, which is a very small fraction of the total vehicle mass. Mass changes due to cargo loading or unloading were only considered to take place at stops and it was assumed that the vehicle load change would not take place for stops less than 20 minutes in duration. These simple criteria allowed potential break points where mass changes might occur in each day's drive cycle to be identified automatically, and the mass estimation could proceed one segment at a time. This approach was programmed to estimate the vehicle mass for each identified driving segment individually. If the mass in two or more sequential segments was found to remain within a specified tolerance, then the segments were joined and the average mass determined for the combined segments.

This process was repeated by the program until the mass for each segment contained in each file was determined. The automated process allowed the mass calculations for all of the files to be performed efficiently. The measured engine energy and values of the estimated tractive energy were plotted for each file processed, and these results were manually reviewed to identify problems with the automated approach. Any discovered anomalies with the mass estimation calculations were corrected by intervening in the calculation.

The mass estimates were compared to several results for which both the tractor and trailer mass were measured directly using an AirWeigh measurement system. (Only a small fraction of data had the trailer mass since only 10 of the 180 trailers owned by the fleet were instrumented with the AirWeigh devices). It was discovered that the mass predicted with this approach was underestimated by approximately 12.6% on average, and this correction was applied to all of the mass estimates before proceeding. The mass distribution based on these estimates is shown in Fig. 2.

The average mass carried, based on a distance-weighted mean, was 24,774 kg (54,618 lbs.). There are some mass levels predicted using this approach that appear incorrect, but the mass estimation is believed to provide a mass that is accurate to within a few thousand kilograms, which gives a reasonable estimate of the overall distribution experienced. The estimated mass variations are helpful in separating different load levels for the drive cycle evaluation. The dashed vertical lines show the mass levels used for separation of the data into low, medium and high mass cases, which were used in developing the synthetic drive cycles. Additional details of the analysis followed can be found in reference [9].

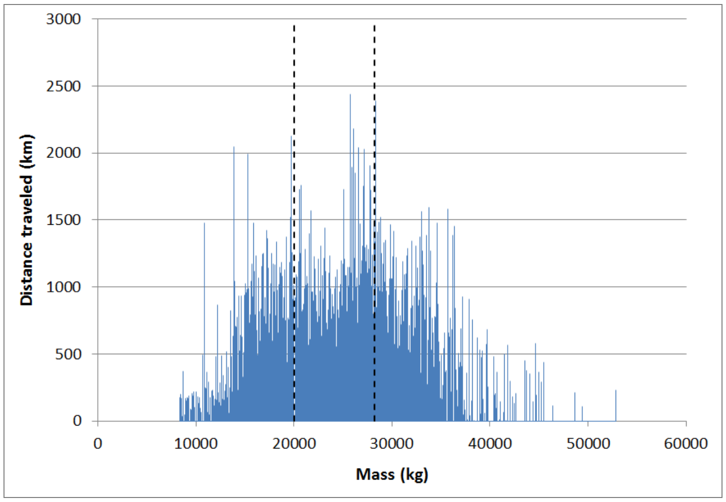

**FIGURE 2 Mass distribution, in terms of the distance travelled at each mass.**

## SYNTHETIC DRIVE CYCLE DEVELOPMENT

The tractive energy is a primary factor in determining fuel consumption, and the tractive power required to move a vehicle forward at each instant in time is determined by the particular operating conditions experienced. The tractive power is given by [8]

$$P_{trac} = mv\frac{dv}{dt} + mgv\sin\theta + \left(C_D A_f\right)\frac{1}{2}\rho v^3 + C_{RR}\, mg\, v, \qquad (1)$$

where $m$ is the vehicle mass, $v$ is the speed, $g$ is the gravitational constant, sin $\theta$ is the grade, $C_D$ is the coefficient of drag, $A_f$ is the vehicle frontal area, $\rho$ is the air density and $C_{RR}$ is the coefficient of tire rolling resistance. It is thus apparent that the combination of speed, acceleration and grade, along with the parameters that characterize the vehicle configuration, uniquely determine the tractive power required at each instant in time. As a direct consequence of this correspondence between the vehicle operating condition and the tractive power, the fuel consumption is determined by the distribution of operating conditions that comprise the vehicle's usage history, i.e. its drive cycle. In reality, driving the same drive cycle multiple times with the same vehicle can result in somewhat different levels of fuel consumption since the driver may not shift at the same points in time, etc., so that even the same vehicle operating conditions can result in different engine operating conditions, which may result in small differences in the fuel consumption. This type of variation is secondary, however, to the tractive energy contributions, and we only address the tractive energy impact on fuel efficiency.

Since a vehicle's fuel efficiency is determined by the ratio of fuel consumed to the distance traveled, the vehicle usage can be scaled without changing the fuel efficiency. If we drive for two hours on flat ground at a steady speed of 80 km/hr. and then for two hours at 100 km/hr., twice as much fuel would be consumed as if we drove only one hour at each speed (all other factors remaining equal). The fuel efficiency (or its reciprocal, the fuel economy) will be the same for either the one-hour or two-hour trip, however, since both the fuel consumption and the distance traveled will change by the same factor. If the same accelerations and decelerations occur during transitions from one speed to another in both cases, or if the fuel consumed in the speed transitions is negligible compared to the steady speed periods, it also would not matter if the higher speed operation occurs first or last. Generalizing these ideas, it can be shown, under the assumptions used in developing the tractive energy model, that two drive cycles will require the same tractive energy (for any given vehicle configuration) if the same set of operating conditions are experienced in both cycles and the fraction of time spent at each operating condition to the total cycle duration is the same in both cycles. This result is the basis for a characterization of drive cycles based on the distribution of all operating conditions experienced. This simple theorem also enables us to develop a drive cycle of a relatively short duration that will give the same fuel efficiency result as would be achieved from a much longer drive cycle (for example, during days or months of travel) simply by matching the distribution of operating conditions from the original drive cycle. This is the fundamental premise for the development of a drive cycle that accurately represents a given set of driving data, and we refer to the shortened cycle as a "synthetic drive cycle" since it represents a synthesis of all of the data contained in the larger set of driving data.

A complete description of the methods and tools developed for creating the synthetic drive cycle is beyond the scope of the present paper, but the basic approach consists of matching the speed vs. acceleration bivariate distribution with that of the original data set. The drive cycle data are loaded initially and each data point (representing a one-second time interval, for this study) is placed into a bin corresponding to the speed and acceleration experienced during each time segment. Each bin is defined in terms of a finite range of speeds and accelerations. The cumulative number of occurrences in each speed-acceleration bin is tracked as all of the data are loaded and analyzed. The end result is a bivariate histogram that represents the total usage in terms of all speed-acceleration conditions experienced. As described above, the overall distribution can be scaled so that the same ratio of operating conditions is experienced in a reduced-duration drive cycle. A desired cycle length is selected for developing the synthetic drive cycle, and the original speed vs. acceleration distribution is scaled accordingly. As part of the drive cycle analysis, driving segments from the original measured data are defined using portions of the measured drive cycle whose endpoints represent local minima and maxima in the elevation data. These drive cycle segments are then used as a set of basis functions—with real speed transients and grade variations—for creation of the synthetic drive cycle. The segments are selected, one by one, to generate the histogram for the synthetic drive cycle in an effort to match the initial scaled bivariate histogram. A search algorithm was developed to identify drive cycle segments whose speed and acceleration data would best "fill in" the synthetic cycle histogram to match the scaled original cycle's histogram. After identifying a set of segments that reasonably matched the target speed-acceleration distribution, the segments are arranged so that the speeds are as continuous as possible. In a final step, the speeds in adjacent drive cycle segments are adjusted as necessary to match the end points in order to create a fully continuous speed trace, and additional drive segments were added where necessary for final matching to the scaled bivariate histogram. Note that the grade data are continuous by construction, since the segments were created using end points where the grade was zero (maxima/minima in elevation). This approach yields a drive cycle whose distribution of speeds and accelerations closely matches that of the original scaled drive cycle and includes real grade variations that are also characteristic of the measure drive cycle data. Reference [9] contains additional details of the method employed.

The bivariate histogram shows the cumulative duration of time that the vehicle was driven at each operating condition. Each bin represents a range of speeds and accelerations, and is defined by discretizing the full range of the speeds and accelerations from the drive cycle. The color of each bin corresponds to the number of times during the drive cycle that the speed and acceleration were within the range represented by that bin. By representing a drive cycle in this manner using the speed-acceleration distribution, the time order of the operating conditions is eliminated. The distribution can also be scaled so that the overall duration is not a factor. Figure 3(a) shows measured driving data from a complete day of driving during which 858.9 km were traveled over 28,787 seconds (about 8 hours) of vehicle operation, while Fig. 3(b) shows the corresponding bivariate speed-acceleration histogram. The scale at the right of the histogram indicates the total time duration experienced at each operating condition in the drive cycle. These measured data were used to generate a synthetic drive cycle with a duration of 1645-seconds. The synthetic cycle representing the original cycle is shown in Fig. 3(c).

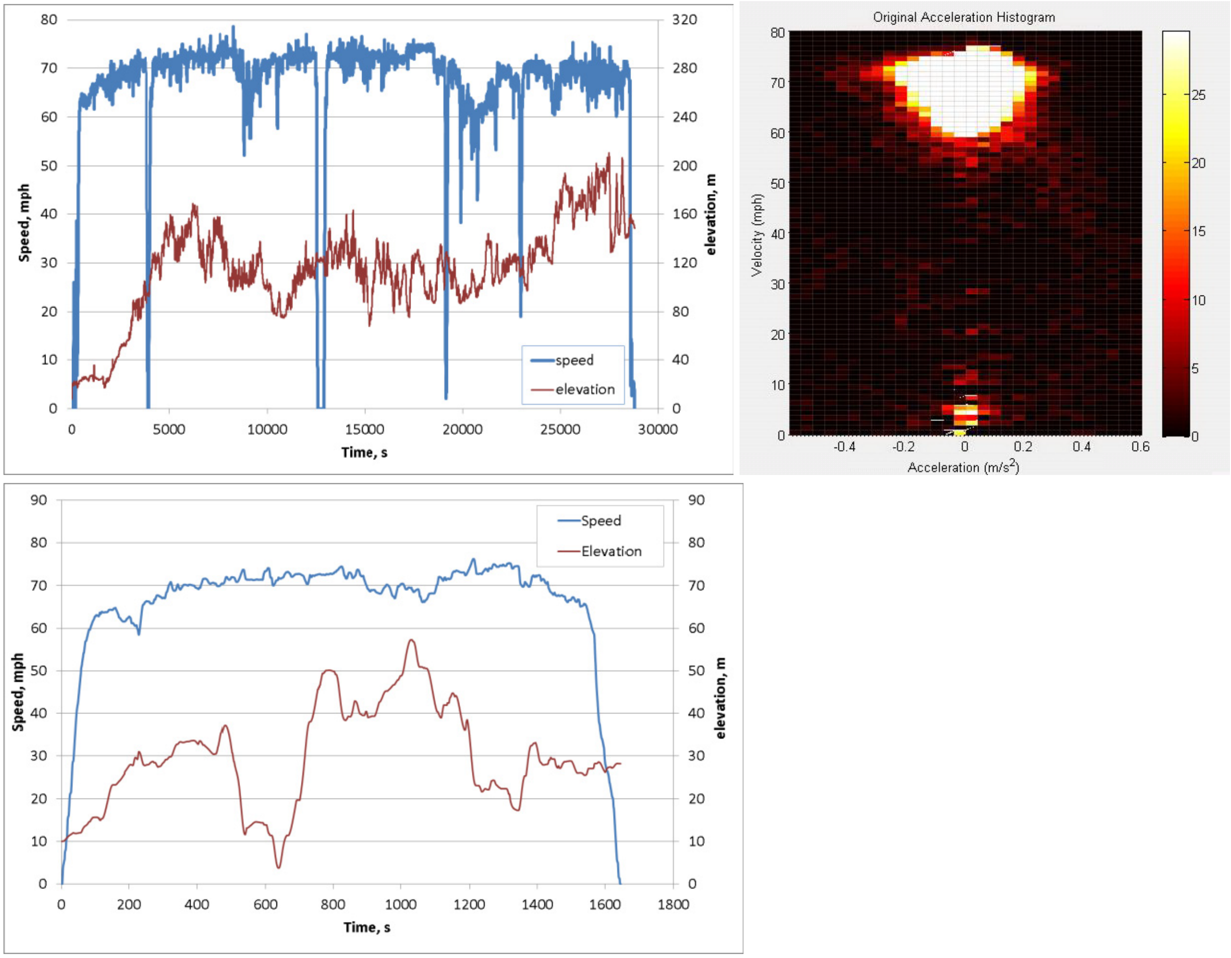

**FIGURE 3 (a) Drive cycle measurement for a complete day of driving, (b) its corresponding acceleration vs. speed bivariate histogram, and (c) the shortened synthetic drive cycle developed from the data.**

Figure 4 compares the bivariate velocity vs. acceleration distributions for the original and synthetic drive cycles shown in Fig. 3. Note that the scale (representing the number of occurrences in the drive cycle within each bin) for the synthetic cycle is less by a factor of approximately 17, corresponding to the reduction in duration of the synthetic cycle. Due to the short duration of the accelerations to and decelerations from highway speeds relative to the length of the rest of the drive cycle, the number of occurrences for each bin in the histograms corresponding to the low-speed accelerations/ decelerations is very low. The bins do not even appear in the histograms when using a normal range of scales, and the low speed range was therefore omitted in Fig. 4. This low incidence of the low speed bins indicates that the corresponding operating conditions are rather insignificant in characterizing the drive cycle.

Figure 4 shows that the histogram for the validation synthetic drive cycle matches the original cycle extremely well for the dominant operating conditions experienced. There are a few bins that differ slightly in magnitude from the original histogram. Since scaling the original cycle's bivariate histogram for the reduced length of the synthetic drive cycle results in bins in the target bivariate histogram that contain non-integer time durations, while the synthetic drive cycle was developed using one-second time intervals, it is not possible to have an identical match between the two cycles. Furthermore, even in cases where a better match may be numerically possible, the process of creating the synthetic cycle with the tools ORNL developed does not always lead to an ideal solution. In spite of the differences between the original and synthetic histograms, the overall agreement between them is considered to be excellent.

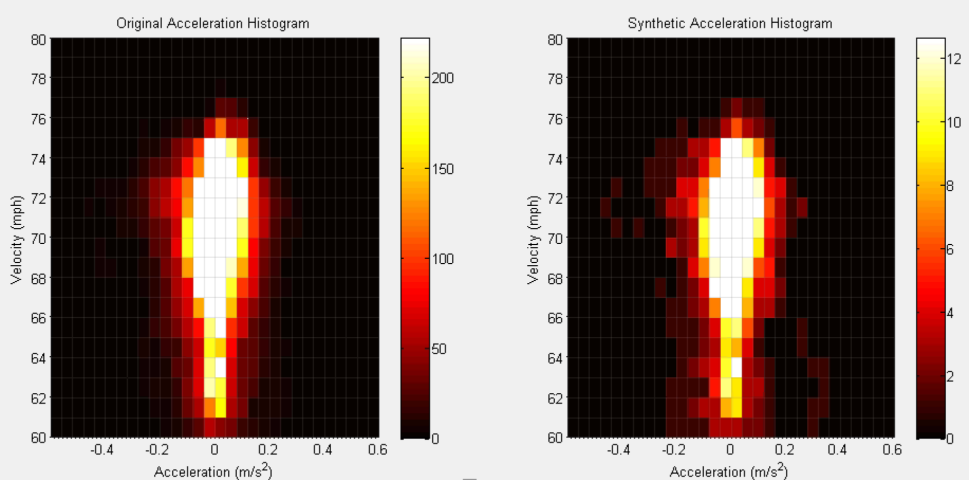

**FIGURE 4 Bivariate histogram of the original driving data and of the synthetic drive cycle developed for the validation.**

The process developed for generating the synthetic drive cycles is quite time consuming since much of the process must be performed manually. Additional research is needed to further develop algorithms used for the synthetic cycle generation, both for optimum matching of the synthetic and original histograms and to create the cycles in a highly automated manner.

## Validation of the Synthetic Drive Cycle Approach

A validation to demonstrate the accuracy of fuel economy results based on the synthetic cycle development was completed by performing simulations of fuel economy using Autonomie vehicle performance software with the two drive cycles shown above, original and synthetic. Autonomie is a plug-and-play vehicle model architecture designed to simulate vehicle performance and evaluate powertrain technologies for improving fuel economy [14]. It estimates fuel consumption by applying a detailed physical representation of all of the major powertrain components on the vehicle, and links the forces required to propel the vehicle with an engine map, which characterizes the fuel consumption of the engine as a function of engine speed and torque. An Autonomie vehicle model has been developed at ORNL to represent the vehicles used in the HTDC study. A heavy duty diesel engine map available in Autonomie was used in the model, but the engine parameters were tuned to be representative of the 15-liter, 6-cylinder Cummins ISX 475 diesel engine that was present on the HTDC test vehicles. The transmission in the model is a 10-speed manual transmission, which is also representative of the tractors with a manual transmission used in the study. The mass simulated in the Autonomie evaluation was 22,000 kg, which was the mass estimated for the measured driving segment. Other parameters in the model were selected to be consistent with those used in the tractive energy analysis. Specifically, the truck's aerodynamic drag coefficient was taken to be 0.62, while a constant value of 0.007 was used for the coefficient of rolling resistance in the analysis. The same vehicle model configuration has been used in prior evaluations to represent the same HTDC test vehicles, and this model has been validated against measured fuel consumption results at ORNL.

The Autonomie model was run for both the original drive cycle and the synthetic cycle, which is intended to closely represent the original cycle. The fuel economy values predicted using the two drive cycles were 5.62 and 5.57 mpg, respectively. This level of consistency in the predicted fuel consumption (within 1%) gives a high level of confidence that the synthetic drive cycle is highly representative of the original cycle and that the fuel economy estimate using a carefully constructed synthetic drive cycle can yield results that are very close to those from the full set of driving data that the synthetic cycle represents.

In addition to performing the fuel economy analysis with Autonomie, the tractive energy model was run using both drive cycles to determine the relative contributions from each energy loss factor to the total tractive energy. The tractive energy model, developed in [8], includes an evaluation of the contributions to the total driving tractive energy from each of several energy loss factors: aerodynamic drag (during driving and braking periods of the drive cycle), rolling resistance (also during driving and braking periods), and from the application of the vehicle's brakes. The reader should refer to [8] for derivations of the five energy loss factors. In the comparisons below, the relative contributions of each energy loss factor to the driving tractive energy are expressed as a percentage of the driving tractive energy. The relative contribution from each energy loss term is strongly dependent on the drive cycle, so this comparison is an excellent test of how well the synthetic cycle matches the original driving data. These terms are also the basis for the energy saving estimates using the tractive energy model, so their accuracy is critical to that of the tractive energy predictions. Table 1 shows the results calculated for the energy loss factors based on the tractive energy model.

**TABLE 1 Comparison of results for the calculated energy loss factors in the tractive energy model, for the original and synthetic drive cycles from the validation case.**

| **Energy Loss Factors (Expressed as a Percentage of the Total Driving Tractive Energy)** | **Original Drive Cycle** | **Synthetic Drive Cycle** |
|---|---|---|
| Aerodynamic drag, driving, $E_{aero,drive}$ | 55.7% | 54.8% |
| Aerodynamic drag, braking, $E_{aero,brake}$ | 3.3% | 2.5% |
| Rolling Resistance, driving, $E_{RR,drive}$ | 35.1% | 34.8% |
| Rolling Resistance, braking, $E_{RR,brake}$ | 2.1% | 1.9% |
| Brakes (associated with the regenerative braking potential), $E_{brakes}$ | 3.0% | 4.0% |

It is found that all of the factors calculated using the synthetic drive cycle are within 1% of those from the original drive cycle, which indicates that the prediction of the fuel saving potential of each advanced efficiency technology (and their combinations) when using the synthetic drive cycle will be very consistent with the result based on the original driving data. Since the elevation changes were not forced to be proportional when creating the synthetic drive cycle, there is a slightly greater increase in the potential energy in the synthetic drive cycle than occurred in the original drive cycle. The fact that the potential energy is non-zero in both cases (it represents 0.8% of the driving tractive energy for the original drive cycle and 2.0% for the synthetic cycle) is the reason that the relative energy contributions of the other terms do not sum to 100%. The impact of this small difference in the potential energy change is minimal on the overall results, although it is responsible for some of the differences appearing in Table 1.

### The Synthetic Drive Cycle Corresponding to the Overall Fleet Usage

Analysis of the drive cycle data corresponding to the low, medium and high mass levels (as indicated by the divisions shown in Fig. 2) was initiated in separate evaluations, but the results from the first stage of analysis showed that there was very little difference in the speeds and accelerations experienced for the three mass levels. It was expected that there would be a non-negligible decrease in accelerations with increasing mass since the power-to-weight ratio decreases with greater load. The data indicated very little difference between the three cases, however, so a single drive cycle developed for the medium mass case was used to analyze all three mass levels. The tractive energy analysis was still repeated for each case separately, however, to account for the impact that the difference in mass has on the fuel efficiency evaluations. Figure 5 shows the comparison of the distributions of speed vs. acceleration for the three mass levels considered. Careful comparison of the three cases does reveal some differences between them, but the overall profiles are surprisingly similar. It is hypothesized that highway conditions, for which most of the range of accelerations are experienced, cause the accelerations to be limited by aerodynamic drag to a point that the mass differences play a relatively minor role. Accelerations also tend to be limited by traffic conditions, so that in many situations it may not be possible to accelerate at the maximum level that the engine is capable of. Another possible mitigating factor is driver training. Since drivers are trained to only accelerate gradually so that the best efficiency can be achieved, this will tend to reduce the higher accelerations that could be achieved when a lower vehicle loading is present. The fact that the class 8 tractor-trailer application operates primarily on the freeway with quite limited low speed operations very likely influenced this effect significantly, since accelerations at lower speeds probably do show greater acceleration variations with load.

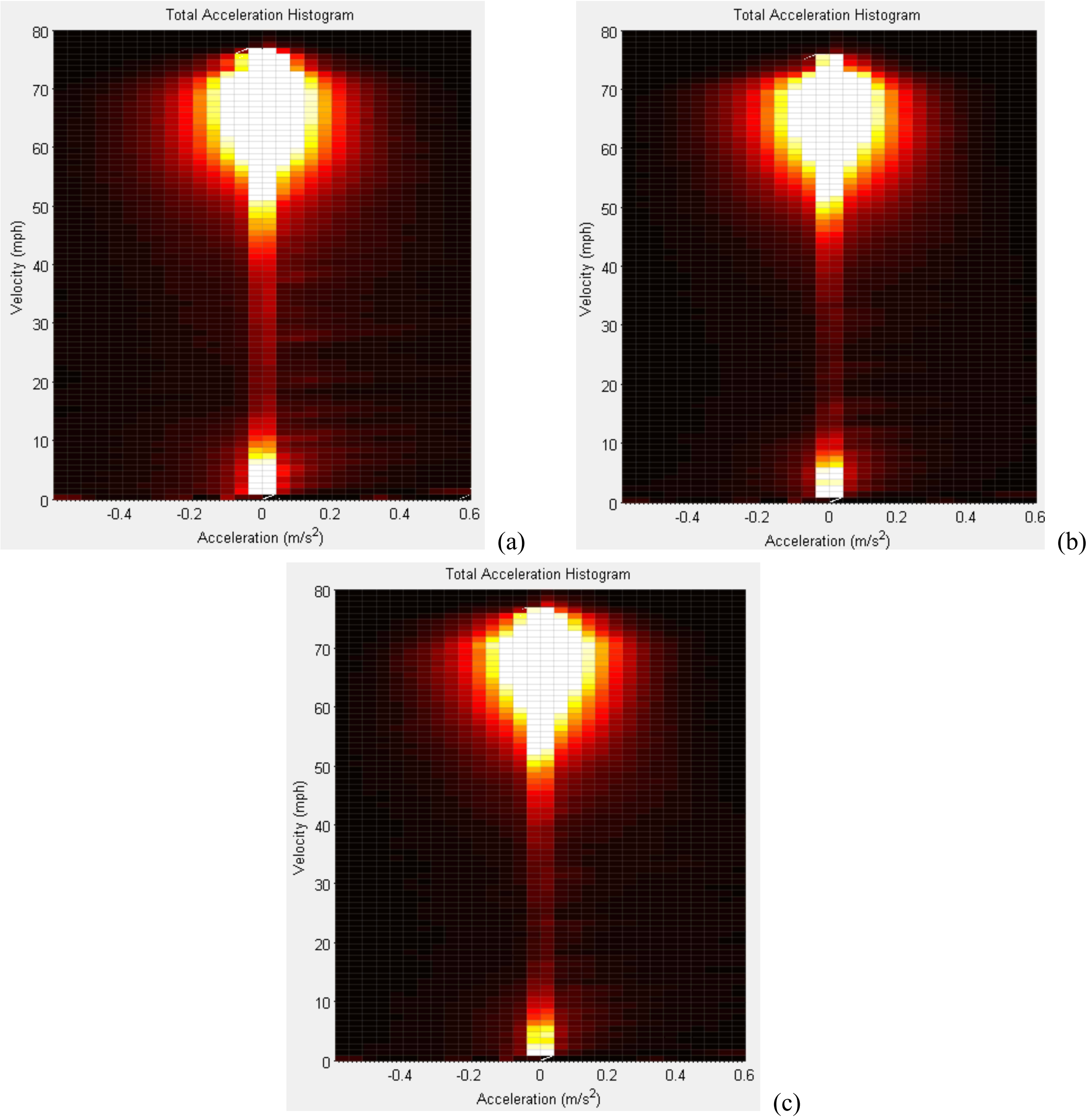

**FIGURE 5 Comparison of the speed vs. acceleration distributions for the low (a), medium (b) and high (c) mass operating conditions.**

It is interesting to observe that the dominant accelerations for the low speed operations are still at very low levels. This effect was examined in some detail to understand the cause and verify that there was not a problem with the software. Since the distribution shown is scaled to only show the operating conditions that are most frequent in the drive cycle, many of the operating points at higher accelerations, while still present, are overwhelmed by the lower acceleration conditions. For a segment of driving such as that analyzed for the validation synthetic cycle from the previous section, the low speed-high acceleration operating conditions are still apparent, even though their contribution to the overall drive cycle is rather limited. When all driving data is included together, however, the periods of driving at relatively steady, low to medium speeds end up being much more significant than the higher acceleration conditions at the same speed. If a truck is driven for just 30 minutes at a speed range of 30-40 mph and maintains a fairly stable speed, this will generate over 1500 seconds of low acceleration conditions for this speed range. This compares to only a few seconds at a time of data within any given speed range that is generated when the truck accelerates from a stop to highway speeds or decelerates rapidly after exiting the highway. There are enough operating conditions on secondary roadways in this application when the trucks drive at steady speeds that this is much more dominant than the high acceleration operations that take place. In the full distribution represented by the speed-acceleration histograms, there are thousands of data points for accelerations up to and beyond the 0.2 m/s$^2$ level, but these thousands of points do not register significantly in comparison to the millions of data points contained in the overall distribution.

One can see an “aura” of low density operating points surrounding the main portions of the drive cycle, but these account for a rather small percentage of the total vehicle usage. Using the statistics of the very large data sets from the HTDC project, the analysis identifies the portions of the drive cycle that are most representative of the overall usage, and it is precisely this information that this drive cycle analysis and synthetic cycle development aims to capture.

The procedure described in the previous section was applied to generate a synthetic drive cycle that represents the overall usage for this trucking fleet’s operation. The medium mass case, which was the largest data set, was used to develop the synthetic drive cycle. The synthetic drive cycle generation using the medium mass case was started before the comparisons were made for the low and high mass cases, and it would have required significant changes to the data to start over using the complete data set for the synthetic cycle creation. Since resources for completing the research were limited, it was decided to proceed with the medium mass distribution, since it is so similar to the total usage and includes over half of the total driving time.

The base synthetic drive cycle is shown in Fig. 6. This was generated using the non-zero speed data initially, although some brief stops were added at the beginning and end of the cycle and after the short micro-trip in the first 100 seconds. The total duration of this drive cycle is 1997 seconds.

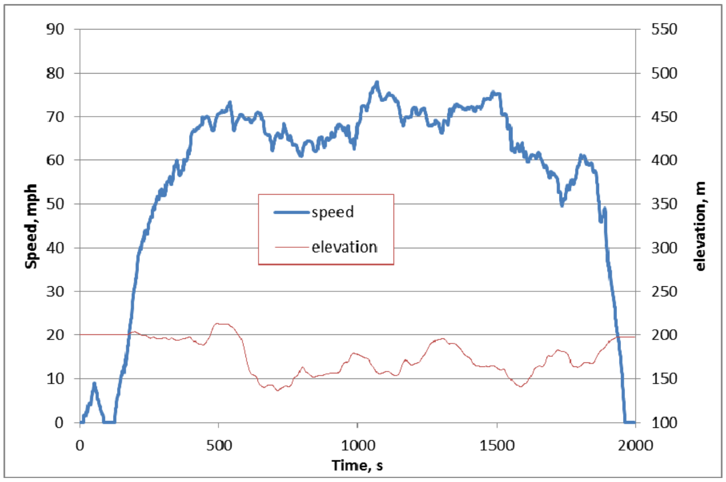

**FIGURE 6 The main synthetic drive cycle, representing the overall usage of the HTDC fleet.**

The bivariate speed-acceleration histogram is shown for the HTDC synthetic drive cycle in Fig. 7, along with the original histogram (on the left side of the figure) that includes all of the driving data corresponding to the medium mass case. As in the case of the synthetic drive cycle development for the validation case, there are a number of bins in the synthetic cycle histogram representing operating conditions that are not evident in the total histogram representing the original data. These points are a result of using 1-second time intervals when creating the synthetic cycle, as discussed in the previous section. The number of such points in the synthetic histogram for this case is a bit higher than in the case of the validation synthetic drive cycle since the complete set of driving data, with the much larger duration of time represented in the original histogram, contains a more broad set of data in all bins of the histogram. Nonetheless, the overall match to the total histogram is excellent: the error between the synthetic cycle and the original drive cycle distribution, based on a sum of squares metric (L2 norm), is less than 2%.

The accelerations and decelerations for the initial speed ramp-up to, and final deceleration from, highway speeds occur at a significantly lower rate than a truck would normally follow, but this provides the lower level accelerations that are representative of the lower speed range. This is an important difference between the synthetic drive cycle and any short-duration measured drive cycle, and this difference in acceleration conditions among the lower speed ranges generates a notable difference in the braking contribution to the total tractive energy, as will be apparent in the next section.

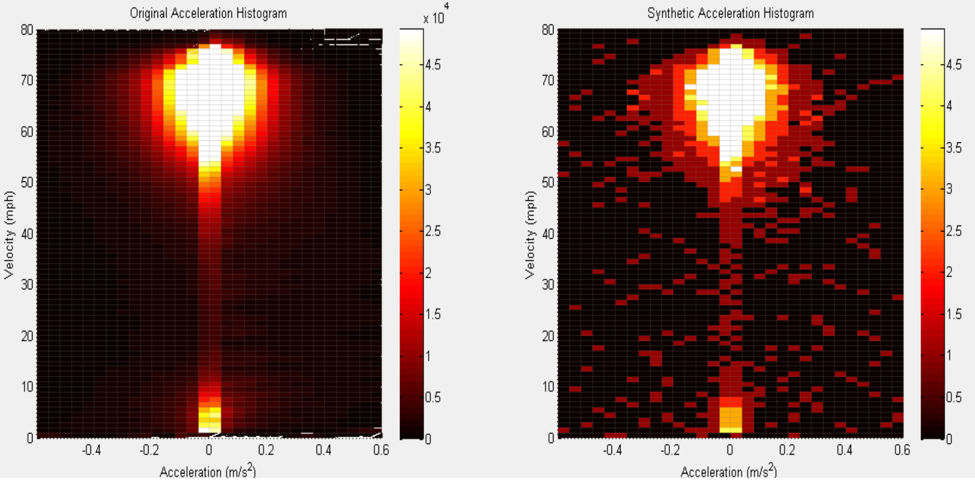

**FIGURE 7 Comparison of the distribution of the synthetic drive cycle and the original histogram containing all of the data from the medium mass operation.**

## CALCULATION OF ENERGY SAVINGS DUE TO VEHICLE EFFICIENCY TECHNOLOGIES

We now present the energy savings results calculated with the tractive energy model based on the synthetic drive cycle representing the fleet's overall usage. The tractive energy model is used to estimate the fuel savings potential from combinations of vehicle efficiency technologies by accounting for reductions in the required tractive energy (the energy required for propulsion at the wheels of the vehicle) over any given drive cycle. The model relies on a variational analysis of the energy losses associated with the vehicle kinematics, and requires only a drive cycle that is representative of the vehicle usage and a small set of vehicle efficiency parameters. The complete development of the tractive energy model is too lengthy for inclusion in the present discussion, but it is presented in reference [8], which should be referenced for a derivation and detailed discussion of the terms presented below.

The results for each of the low, medium and high mass cases were calculated separately, and the results were then combined based on a distance-based weighting of each mass case. The combined result—including the contributions to the total driving tractive energy ($E_{trac,drive}$) due to tire rolling resistance during both driving ($E_{RR,drive}$) and braking ($E_{RR,brake}$) conditions, aerodynamic drag in driving ($E_{aero,drive}$) and braking ($E_{aero,brake}$) conditions, and due to mechanical braking ($E_{brakes}$)—is presented in

Table 2. These terms are calculated as an intermediate result in the tractive energy model and are the controlling factors in determining the fuel savings potential associated with each advanced efficiency technology.

**TABLE 2 The Contributions to the Driving Tractive Energy from each Energy Loss Factor for the Overall, Combined Fleet Usage, Based on the Synthetic Drive Cycle**

| Tractive Energy Contribution | Calculated Energy (MJ) | Percent of $E_{trac,drive}$ |
|---|---|---|
| $E_{aero,drive}$ | 93.65 | 43.3% |
| $E_{aero,brake}$ | 12.77 | 5.9% |
| $E_{RR,drive}$ | 74.63 | 34.5% |
| $E_{RR,brake}$ | 11.19 | 5.2% |
| $E_{brakes}$ | 23.87 | 11.0% |
| $E_{trac,drive}$ (total driving tractive energy at default operating condition) | 216.11 | 100% |
| $E_{trac,drive}$ (with mass reduced 2000kg) | 206.29 | 95.5% |

Figure 8 shows the fuel savings estimated with the tractive energy model based on the vehicle parameters and reductions shown in Table 3. The fuel savings benefits due to the different technologies are cumulative within each of the two configurations (with or without regenerative braking), so combinations of technologies can be easily evaluated using the tractive energy results. It should be noted that these estimates are not based on an implementation of specific devices or hardware, but represent the fuel savings that would be realized when the corresponding vehicle energy loss parameters are reduced by the levels shown. The selected parameters are intended to represent typical performance gains for state-of-the-art fuel savings technologies relative to an approximately average class 8 tractor-trailer configuration, but a characterization of specific hardware is needed to evaluate the potential fuel savings on a case-by-case basis.

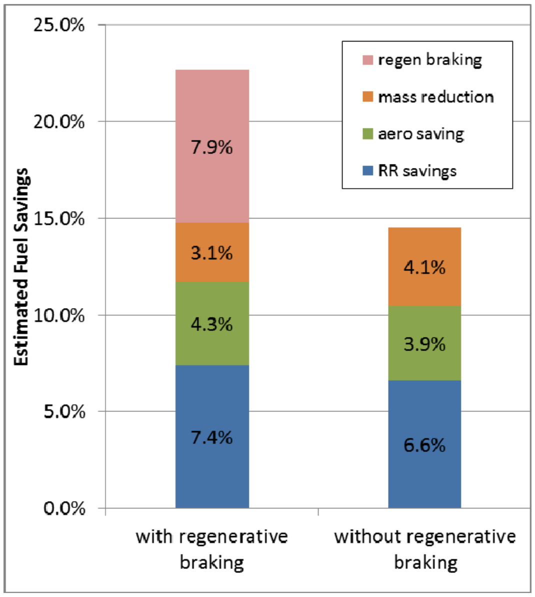

**FIGURE 8 Fuel savings estimate for combinations of advanced efficiency technologies for the combined usage in the HTDC fleet.**

**TABLE 3 Vehicle parameter values used in the tractive energy analysis**

| | **Aerodynamic drag coefficient, $C_d$** | **Coefficient of rolling resistance, $C_{RR}$** | **Mass (kg)** | **engine thermal efficiency, $\eta_{eng}$** | **transmission efficiency, $\eta_{trans}$** | **regen braking efficiency, $\eta_{regen}$** |
|---|---|---|---|---|---|---|
| Parameter values | 0.62 | 0.007<br>(7 kg/ton) | 24,774 | 0.42 | 0.90 | 0.80 |
| Reduction applied | 0.062<br>(10%) | 0.0015<br>(1.5 kg/ton) | 2000 | N/A | N/A | N/A |

## SUMMARY/CONCLUSIONS

A comprehensive approach was presented for the development of a synthetic drive cycle that is highly representative of a large set of measured drive cycle data. The results of an in-depth analysis of drive cycle measurements from a class 8 regional freight delivery fleet were presented to demonstrate the approach, and the synthetic drive cycle was used in a tractive energy analysis to estimate the fuel savings benefits that can be achieved with various combinations of fuel efficiency technologies. A comparison of the results shown in Table 1 with those from Table 2 reveals that rather significant differences can exist between the tractive energy contributions for a single day's drive cycle and for the characteristic drive cycle representing the complete fleet usage. This result underscores the importance of using appropriate drive cycles in both analysis and testing in order to accurately estimate fuel consumption for a particular usage and to correctly quantify the fuel savings that will be achieved by implementing new technologies.

The approach developed in this research assures that large quantities of drive cycle data characterizing a particular usage are very well represented in the form of the synthetic drive cycle since the same distribution of speeds and accelerations are present in the synthetic drive cycle as in the original data set. A validation of the synthetic drive cycle methodology resulted in a predicted fuel economy that was within 1% of that calculated using the original drive cycle. Furthermore, the distribution of the 5 energy loss factors that comprise the tractive energy were very consistent (all within 1% of the original values) between an 8-hour measured drive cycle and a 1645-second synthetic drive cycle created to represent the original. The generation of the synthetic drive cycle, however, requires a considerable amount of user interaction and is rather time consuming, and further research is needed to develop a highly automated process for generating synthetic drive cycles.

The savings in fuel consumption predicted by the tractive energy model for this class 8 tractor-trailer fleet are rather impressive for the technologies considered. By implementing the rolling resistance and aerodynamic drag technologies, which can be done as retrofits to existing vehicles, over a 10% improvement in fuel economy can be achieved, based on the assumptions for the vehicle parameter changes. The reduction in the rolling resistance coefficient by 0.0015, or 1.5 kg/ton, used in this analysis depends on the initial and final set of tires used on the vehicle, but this level of reduction is very typical, if not on the conservative side, when replacing typical dual tires with new generation wide-base single (NGWBS) tires. Similarly, the 10% reduction in aerodynamic drag coefficient used in the analysis seems to be rather typical based on results that have been reported for fuel efficiency gains when using aerodynamic drag reduction devices. Vehicle lightweighting, while it represents a change in vehicle design that must be implemented for new vehicles, can also yield quite significant fuel savings, and research and development of lighter materials and manufacturing methods that can reduce truck mass should be pursued by vehicle manufacturers and the transportation research community. The predicted benefits of the use of a regenerative braking system in this tractor-trailer application are quite impressive. For the overall usage of this fleet, regenerative braking is predicted to reduce fuel consumption by nearly 8%, and if low rolling resistance tires and aerodynamic drag reductions are used at the same time, the regenerative braking increases the benefits by an additional 1.2%. The results were not presented for the high mass case separately, but if a fleet operates at higher average mass levels (i.e. carrying heavier loads), the hybrid savings were found to exceed 10%. These levels of fuel savings suggest that further study of hybridization of class 8 tractor-trailers is well warranted. Clearly, the cost of each technology is a critical factor in making a purchase decision since the vehicle owner must ultimately bear the costs of deploying any advanced efficiency technologies, and the benefits must justify the additional costs. The results of this study enable a detailed cost-benefit analysis for the implementation of specific technologies when their performance is characterized in terms of the basic vehicle parameters.

The approach presented here holds significant potential for individual fleets to estimate the fuel savings that can be achieved with their specific usage, and it can also be beneficial in evaluating entire classes or applications of heavy-duty trucks. For the development of truck fuel efficiency standards and evaluation of the impact of advanced efficiency technologies, the results of the present research are useful in evaluating the fuel economy and CO2 emissions reductions that can be expected in class 8 tractor-trailers used in regional LTL service. The same analysis approach could also provide further insight in other vehicle applications. Further research is needed, however, to develop methodologies and tools that will streamline the process of generating a synthetic drive cycle since it is currently quite time-consuming and requires specialized skills that would not likely be present in most trucking fleets.

## ACKNOWLEDGEMENTS

This project was sponsored by the National Highway Traffic Safety Administration (NHTSA). The authors wish to thank Ken Katz, Lead Engineer, CAFE, for funding and supporting this research.

## REFERENCES

1. Davis, S.C., S.W. Diegel, R.G. Boundy. *Transportation Energy Data Book*, Edition 31. Oak Ridge National Laboratory, Oak Ridge, Tenn., 2012.
2. U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA), DOT. *Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule*. 49 CFR Parts 523, 534, and 535, 2011.
3. Sovran, G. and D. Blaser. A Contribution to Understanding Automotive Fuel Economy and Its Limits. SAE Technical Paper 2003-01-2070, 2003.
4. Sovran, G. and M.S. Bohn. Formulae for the Tractive-Energy Requirements of Vehicles Driving the EPA Schedules. SAE Technical Paper 810184, 1981.
5. An, F. and M. Ross. A model of fuel economy and driving patterns. SAE Paper 930328, 1993.
6. Capps, G., O. Franzese, B. Knee, M.B. Lascurain and P. Otaduy. *Class-8 Heavy Truck Duty Cycle Project Final Report*. Report No. ORNL/TM-2008/122. Oak Ridge National Laboratory, 2008.
7. Lascurain, M.B., O. Franzese, G. Capps, A. Siekmann, N. Thomas, T. LaClair, A. Barker, and H. Knee. *Medium Truck Duty Cycle Data from Real-World Driving Environments: Project Final Report*, Report No. ORNL/TM-2012/240. Oak Ridge National Laboratory, 2012. http://info.ornl.gov/sites/publications/files/Pub39145.pdf, accessed July 26, 2013.

8. LaClair, T. Application of a Tractive Energy Analysis to Quantify the Benefits of Advanced Efficiency Technologies for Medium- and Heavy-Duty Trucks Using Characteristic Drive Cycle Data. *SAE Int. J. Commer. Veh.* Vol. 5, No. 1, 2012, pp. 141-163.
9. LaClair, T., Z. Gao, A. Siekmann, J. Fu, J. Calcagno and J. Yun. *Truck Technology Efficiency Assessment (TTEA) Project Final Report*, Report No. ORNL/TM-2012/586, Oak Ridge National Laboratory, 2012. http://info.ornl.gov/sites/publications/files/Pub40546.pdf, accessed July 26, 2013.
10. Department of Defense. *Global Positioning System Standard Positioning Service Performance Standard*, 4th Edition, September 2008. http://www.navcen.uscg.gov/pdf/gps/geninfo/2008SPSPerformanceStandardFINAL.pdf, accessed July 26, 2013.
11. Boriboonsomsin, K. and M. Barth. Impacts of Road Grade on Fuel Consumption and Carbon Dioxide Emissions Evidenced by Use of Advanced Navigation Systems. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2139*, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 21-30.
12. Boroujeni, B., H. Frey, and G. Sandhu. Road Grade Measurement Using In-Vehicle, Stand-Alone GPS with Barometric Altimeter." *J. Transp. Eng.*, Vol. 139, No. 6, 2013, pp. 605–611.
13. American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets*, 6th Edition. AASHTO, 2011.
14. Argonne National Laboratory. *Autonomie*. http://www.autonomie.net, accessed July 26, 2013.