

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

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ABSTRACT

Accurately predicting the fuel savings that can be achieved with the implementation of various technologies developed for fuel efficiency can be very challenging, particularly when considering combinations of technologies. Differences in the usage of highway vehicles can strongly influence the benefits realized with any given technology, which makes generalizations about fuel savings inappropriate for different vehicle applications. A model has been developed to estimate the potential for reducing fuel consumption when advanced efficiency technologies, or combinations of these technologies, are employed on highway vehicles, particularly medium- and heavy-duty trucks. The approach is based on a tractive energy analysis applied to drive cycles representative of the vehicle usage, and the analysis specifically accounts for individual energy loss factors that characterize the technologies of interest. This tractive energy evaluation is demonstrated by analyzing measured drive cycles from a long-haul trucking fleet and the results of an assessment of the fuel savings potential for combinations of technologies are presented. The results of this research will enable more reliable estimates of the fuel savings benefits that can be realized with particular technologies and technology combinations for individual trucking applications so that decision makers can make informed investment decisions for the implementation of advanced efficiency technologies.

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INTRODUCTION

For vehicle technologies aimed at improving fuel economy, it is desirable from a user's perspective to be able to estimate the fuel savings that can be achieved when using a given technology, and this should correspond to the particular usage of the vehicle so that decisions can be made with respect to the fuel savings benefits in actual use vs. the cost of implementing the technology. Vehicle usage, as characterized by a representative vehicle drive cycle, can differ greatly between different vehicle applications and the fuel economy can be rather strongly dependent on the drive cycle followed [1,2]. As a result, there is no "one size fits all" test or analysis that can be performed to quantify the fuel savings potential of a given technology without knowledge of the drive cycle. A technology that is very effective in one vehicle application may provide little or no fuel savings in another application with a very different usage. In the trucking industry in particular, vehicle usage can vary dramatically from one application to another. Among the numerous vehicle types and trucking applications, there is a

complete spectrum of usage ranging from nearly constant highway speed operation, as is typical for a long-haul freight carrier, to operation at very low average speed with frequent stops and accelerations, as in the case of urban refuse trucks or buses. The fact that fuel efficiency benefits can be drive cycle dependent can therefore cause a high level of uncertainty associated with the expected benefits of a new technology for different applications/vocations. Due to the high cost of implementing most advanced vehicle technologies, this difficulty in assessing their benefits can lead to delays in deploying new technologies in the marketplace, even when the benefits may be significant, since fleets or owner-operators are not generally willing to make an investment without knowing the payoff in terms of fuel savings. In addition to these issues, it is noted that quantifying the benefits of vehicle efficiency technologies can be more challenging if more than one technology is considered together. For combinations of multiple fuel saving technologies on the same vehicle, it is possible to have interactions with respect to the fuel benefits so that the

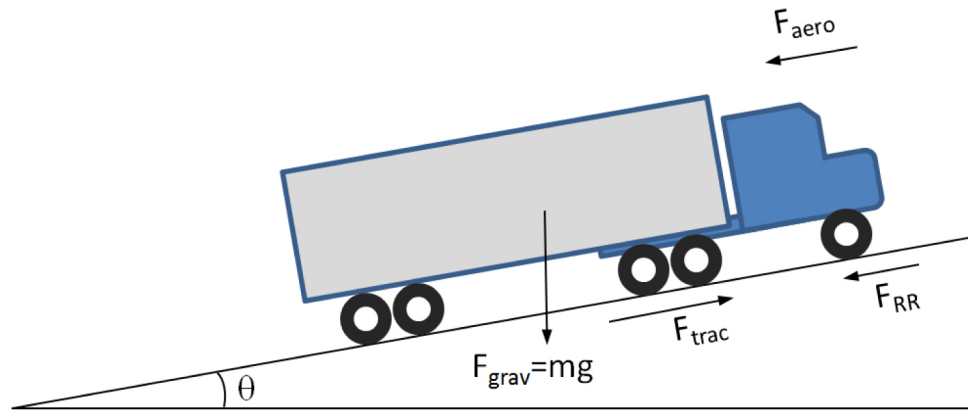


Figure 1. Free-body diagram of a truck driving on a roadway.

reduction in fuel consumption of a combination of technologies may not simply be the sum of the fuel savings that each technology provides individually.

This paper presents a new model to quantify the fuel savings potential of individual and combined vehicle technologies through the use of a tractive energy analysis. As a starting point for the analysis, it is assumed that a drive cycle that is characteristic of the vehicle application is available. The drive cycle definition can include an elevation profile in addition to the traditional speed profile. The basic tractive energy analysis follows an approach that several researchers have used in the past [2,3,4], but by accounting separately for the contributions from various energy loss factors to the driving tractive energy, a differential analysis is developed that can be used to estimate the potential for fuel savings from a range of fuel efficiency technologies. Once the various contributions to the tractive energy are evaluated for the specified drive cycle, it is quite straightforward to evaluate the fuel savings potential for any combination of the technologies considered. The analysis presented is a first order model that predicts the fuel savings potential of these technologies, both individually and in combinations. The model uses very simple parameters to characterize the technologies, but further refinements to the approach could be implemented to provide more detailed estimates when specific characterizations of the technologies are available.

FUNDAMENTAL CONSIDERATIONS

The objective of this analysis is to develop a simple approach to estimate the fuel savings potential of advanced fuel efficiency technologies that act upon the tractive energy requirements of the vehicle. Most fuel savings technologies function by reducing parasitic energy losses that a vehicle must overcome, and each technology has certain energy losses that they reduce or recover (e.g. aerodynamic drag, tire rolling resistance, braking energy losses, drivetrain frictional losses, or accessory power consumption). Analyzing the tractive energy input needed to overcome the various forces acting on the vehicle and accounting for the contribution of different parasitic losses during different regimes of the drive

cycle provides a means to assess the energy savings potential of these technologies.

TRACTIVE ENERGY DURING DIFFERENT PERIODS OF VEHICLE OPERATION

The force acting at the interface between a vehicle and the ground (by means of driving and braking forces generated by the tires) is referred to as the *tractive force*, and it is this force that serves to accelerate (or decelerate) a vehicle, overcome the forces of aerodynamic drag and tire rolling resistance, and in the case of driving up a hill, to propel the vehicle up a grade. When a vehicle is being actively propelled and the engine is needed to provide power to the wheels the tractive force is positive, while the tractive force is negative during periods of braking or engine braking. The mechanical energy associated with generation of the tractive force is called the *tractive energy* and the corresponding instantaneous power requirement is the *tractive power*. The tractive energy can be calculated from knowledge of the forces acting on the vehicle over any distance traveled. The tractive energy provides a measure of the total mechanical energy required to follow a given drive cycle, and it plays an important role in the fuel consumption of a vehicle [2,3,4]. It should be apparent that additional fuel is generally required for a drive cycle with higher tractive energy requirements, but not all energy contributors to the total tractive energy have the same impact on fuel consumption, as will be illustrated below.

Figure 1 is a force-body diagram of a truck while it is driven on the highway. The forces acting on the truck are the rolling resistance, the aerodynamic drag, and the gravitational body force, which depends on the slope of the roadway.

This figure represents a general case covering all regimes of operation, depending on the value of the slope and the direction of the tractive force. Applying Newton's 2nd law of motion results in the following equation:

$$F_{trac} = m \frac{dv}{dt} + mg \sin \theta + F_{aero} + F_{RR}, \quad (1)$$

A key aspect of this analysis is distinguishing between the periods of driving and braking tractive force throughout the drive cycle. Equation (1) provides the criteria to determine when the tractive force is driving (positive):

$$\frac{dv}{dt} > -g \sin \theta - \frac{F_{aero} + F_{RR}}{m}. \quad (2a)$$

and when the tractive force is braking:

$$\frac{dv}{dt} < -g \sin \theta - \frac{F_{aero} + F_{RR}}{m}. \quad (2b)$$

Multiplying Eq. (1) by the vehicle speed, we arrive at the relation for the tractive power,

$$P_{trac} = mv \frac{dv}{dt} + mgv \sin \theta + P_{aero} + P_{RR}, \quad (3)$$

where the power terms, P_{trac} , P_{aero} and P_{RR} are given as the product of the respective force and the vehicle's speed. We note that $v \sin \theta$ is the rate of change of elevation, $\frac{dh}{dt}$, of the vehicle. Integrating Eq. (3) with respect to time between times t_0 and t_1 yields the expression for the tractive energy required to travel the distance traversed over that time period.

$$\begin{aligned} \Delta E_{trac} &= \frac{1}{2}m(v_2^2 - v_1^2) + mg(h_2 - h_1) + \Delta E_{aero} + \Delta E_{RR} \\ &= \Delta E_{kinetic} + \Delta E_{potential} + \Delta E_{aero} + \Delta E_{RR} \end{aligned} \quad (4)$$

There are several different factors that contribute to the overall tractive energy requirement over a drive cycle. Several of these factors are dissipative in nature (rolling resistance, aerodynamic drag and vehicle braking, including engine braking) while others represent reversible energy contributions (kinetic and potential energy). Distinguishing between these contributions and accounting individually for the dissipative energy terms over different driving regimes can give a strong indication of where significant energy savings can be achieved. For such an analysis, it is critical that we differentiate between the net tractive energy and the driving tractive energy inputs during the drive cycle. Only positive tractive energy inputs require additional fuel energy inputs to the engine, and two drive cycles that have the same net tractive energy can have very different driving tractive energy contributions. For a conventional vehicle that does not have regenerative braking capabilities, the difference in driving tractive energy will cause the fuel consumption to be very different between the two cycles. The driving tractive energy is defined by integrating the tractive power only for

periods of time when the tractive force is positive. We define the driving tractive energy,

$$E_{trac,drive} = \int_{t_{drive}} P_{trac} dt \quad (5a)$$

where it is understood that the integration is performed over the set of times, t_{drive} , for which Eq. (2a) is satisfied. For the energy that goes into braking the vehicle, the corresponding equation is

$$E_{trac,brake} = - \int_{t_{brake}} P_{trac} dt. \quad (5b)$$

We have defined $E_{trac,brake}$ using the negative of the integral so that the resulting value is positive. The net tractive energy is given by Eq. (4), evaluated over the entire drive cycle, and it should be clear that $E_{trac,net} = E_{trac,drive} - E_{trac,brake}$.

Although kinetic and potential energy are reversible and do not affect the net tractive energy, braking represents a dissipative force that depletes the energy that is effectively stored as kinetic and potential energy. In effect, the brakes consume additional energy that could be used to move the vehicle further down the road if the vehicle were allowed to coast or if the energy were stored and recovered, as is done with a hybrid vehicle. Beyond the consideration of hybrid vehicles, there is a more subtle role that braking plays in fuel economy with respect to the benefits that can be obtained from advanced fuel efficiency technologies. The need to decelerate the vehicle by using the brakes can have a negative impact on the energy savings attainable by using energy efficiency technologies other than regenerative braking. Consider, for example, the energy losses associated with braking if a vehicle uses low rolling resistance tires. There is an energy savings associated with the low rolling resistance when the vehicle cruises at steady speeds, which will lower the energy inputs required during these periods of driving. However, during the periods of braking, if we assume that the same speed will be followed, the lower dissipative force associated with the low rolling resistance tires results in higher required braking forces during the decelerations. This means that, for the periods of braking, all of the energy savings due to the low rolling resistance tires is simply lost through additional braking requirements on a traditional vehicle. Therefore, during any periods of braking, there is no energy saving benefit from the use of the low rolling resistance tires, and for drive cycles that include significant periods of braking, the fuel savings due to low rolling resistance is much lower than for drive cycles in which there is minimal braking. Technologies that reduce the aerodynamic drag or transmission energy losses will have a

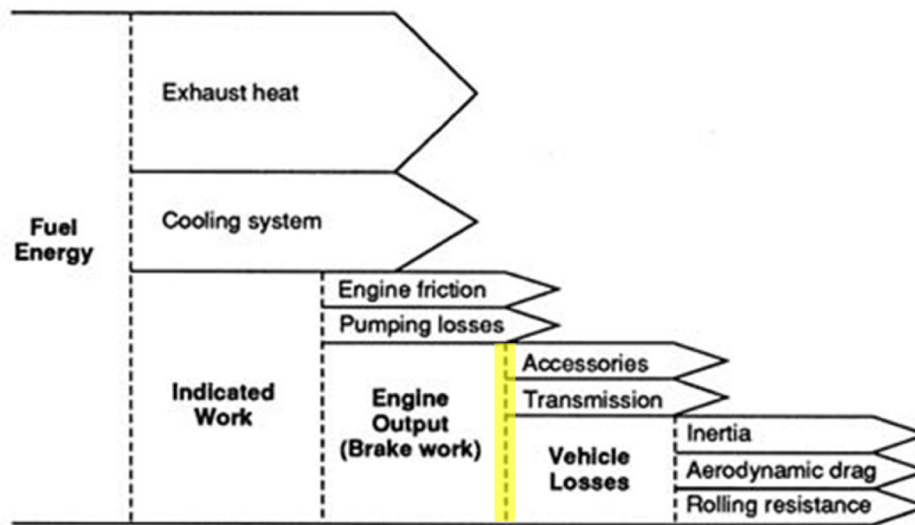


Figure 2. Typical fuel energy distribution for a vehicle operating on a level road (modified from [5]). Reprinted with permission from the National Academies Press, Copyright 1992, National Academy of Sciences.

similar reduced benefit for drive cycles with significant periods of braking.

VEHICLE FUEL CONSUMPTION

To develop a better understanding of the role of tractive energy on fuel consumption, it is useful to consider the energy losses internal to the vehicle, both in the engine and through the rest of the drivetrain. This section presents a review of the energy conversion processes and energy losses associated with normal vehicle operation, and it further develops the justification for application of the tractive energy analysis.

Fig. 2 shows a basic accounting of the energy used in a vehicle [5], starting with the fuel energy and considering the conversion of the thermal energy to work, the energy losses that occur within the engine and drivetrain and ultimately the energy used to propel the vehicle. Each box in the figure represents the energy present at a given state of the drivetrain. The areas with the arrow-shaped regions represent energy losses or the use of energy that occurs during the process corresponding to the preceding box. This figure was developed to graphically represent how the overall energy use is distributed in the vehicle, and the height of each energy term shown in the figure is in approximate proportion to the actual energy use. The relative contributions, however, can vary among different vehicle applications. The processes and energy terms shown to the left of the highlighted line occur within the engine, while everything to the right is associated with mechanical energy transmission and dissipative losses that occur downstream of the engine in the driveline. The net mechanical energy produced by the engine is what is available at the drive shaft in order to perform the primary tasks the engine must perform. This is often referred to as “brake work,” as indicated in the figure.

Most of the energy loss that takes place in the conversion of the fuel energy to mechanical energy is due to thermodynamic irreversibility, and to first order, the mechanical energy produced is proportional to the fuel energy. The engine's operating load and speed do have an impact on the efficiency of the energy conversion process, but the efficiency range is relatively narrow, particularly for conditions that are typical during normal driving. The present analysis assumes that the fuel consumption corresponding to the drive cycle followed is proportional to the total mechanical energy required during all periods of *positive* tractive force. This is expressed by the following equation:

$$W_{brake,drive} = \eta_{engine} E_{fuel,drive}. \quad (6)$$

The term $W_{brake,drive}$ in Eq. (6) is the mechanical energy output from the engine during periods of driving tractive power output over the drive cycle; $E_{fuel,drive}$ is the corresponding fuel energy; and η_{engine} is an engine thermal efficiency, which is assumed to be constant. (A typical value for η_{engine} is taken to be 0.42 throughout this analysis, which is representative of modern heavy-duty diesel engines.) Refinements to this assumption could be made in the model based on a linearization of the engine efficiency as a function of engine speed and load (as in [4]), but it would require knowledge of specific gear ratios in the drivetrain, and gear shifting points would have to be assumed in order to implement this approach for a given vehicle and drive cycle. While the latter approach is more rigorous, the added complexity would reduce the intended generality of this first order model and has been found to be unnecessary to obtain results that quantify reasonably well the fuel saving potential of different efficiency technologies.

Returning to Fig. 2, we now consider energy losses that occur downstream of the engine. The mechanical energy output from the engine is reduced further before reaching the wheels. The engine must provide energy to various accessories of the vehicle, such as the alternator, engine fan and the cabin climate control system. The energy use associated with operating the accessories normally varies in time, but an average power value is often used in analysis. This approach has been found to provide good results for predicting the total fuel consumption even for high fidelity vehicle performance models [6,7]. This analysis therefore assumes an average accessory power use, and the energy for accessories is deducted directly from the engine brake work. It is noted that the energy requirements for accessories can vary significantly among different vehicle applications [8] or even during different times of the year for climate control functions. Therefore, a representative accessory load is needed to accurately predict the total fuel consumption. The effect of accessory load levels on the fuel savings associated with changes in the tractive energy contributions, however, is relatively minor in most cases. A second mechanical energy loss occurs in the transmission due to frictional losses in the gears, differential, bearings, etc. These losses are approximately proportional to the power transmitted, with approximately 90% of the energy transmitted to the wheels. It is therefore assumed that the transmission efficiency is constant. These two assumptions result in the following equation relating the brake energy and the tractive energy:

$$E_{trac} = \eta_{trans} (W_{brake} - E_{access}), \quad (7)$$

where η_{trans} is the overall driveline efficiency and E_{access} is the energy consumption of the accessories.

The energy required to overcome inertial forces, aerodynamic drag, and tire rolling resistance, which are shown at the bottom right of Fig. 2, represents the full required tractive energy to drive on a flat roadway (energy corresponding to gravitational forces also needs to be considered for operations on a grade). It is seen in the figure that the tractive energy actually represents a relatively small portion of the total fuel energy use. It should be noted that propulsion is generally the primary purpose for operating a vehicle, although in certain situations or during certain periods of operation, running the accessories may be the main objective, such as when the engine drives a compressor or hydraulic system for a vocational work truck. For the purpose of this study, we shall limit our consideration primarily to periods when the vehicle is being driven and the main energy use is to propel the vehicle along with the load it is carrying. It should be apparent that if the demanded tractive energy is reduced as a result of reduced aerodynamic drag, rolling resistance or other factors while following the same drive cycle, there will be a corresponding reduction in the upstream energy losses. As a consequence, the fuel energy is reduced in a nearly proportional manner to reductions in the required tractive energy. Based on the arguments made above and the

assumptions that we have outlined, the fuel energy can be related to the tractive energy through the following relationship:

$$E_{trac,drive} = \eta_{trans} (\eta_{engine} E_{fuel,drive} - E_{access,drive}), \quad (8)$$

An important consequence of this is that the change in the fuel energy requirement associated with tractive energy changes is constant, i.e.

$$\frac{dE_{fuel}}{dE_{trac}} = \frac{1}{\eta_{trans} \eta_{engine}}. \quad (9)$$

This result, which shows that any reduction in the positive tractive energy will generate a proportional savings in fuel consumption, is an important conclusion that forms a basis for all of the remaining analysis. This result also confirms the approach of accounting separately for the savings in the driving tractive energy associated with individual technologies.

Some assumptions used in the derivation above are not based on rigorous theoretical concepts, and the reader may question how appropriate it is to use the assumptions made. Before proceeding with the remainder of the development and analysis, a sample result from the drive cycle evaluations is presented to demonstrate the adequacy of the above assumptions and the primary conclusion. Figure 3 shows a measured speed cycle of a class 8 tractor-trailer, along with the measured cumulative fuel consumption during periods of driving tractive power. The fuel consumption during periods when the vehicle is idling is not included, and the calculated driving tractive energy. The selected drive cycle includes a variety of driving conditions, including nearly constant-speed highway operation as well as periods of more urban driving during which frequent speed changes occur. Although the fuel rate and tractive power vary significantly during different periods of the drive cycle, it can be seen that the fuel consumption increases in a very similar manner to the driving tractive energy.

To show the relationship more clearly, the cumulative fuel consumption (during positive tractive power periods) is cross-plotted against the tractive energy requirement during the drive cycle in Fig. 4. Note that the tractive power is calculated from the drive cycle, whereas the fuel consumption is a measured value, so this is not a model result, but rather a validation of the approach. This result shows that the trend is indeed very linear throughout the drive cycle, even with the very different driving styles experienced during the approximately 3-hour drive cycle. This verifies the relevance of the assumptions made and validates the appropriateness of using the tractive energy to estimate fuel savings. Numerous drive cycles measured from several different trucks have been evaluated at the Oak Ridge National Laboratory as part of this study, and the same

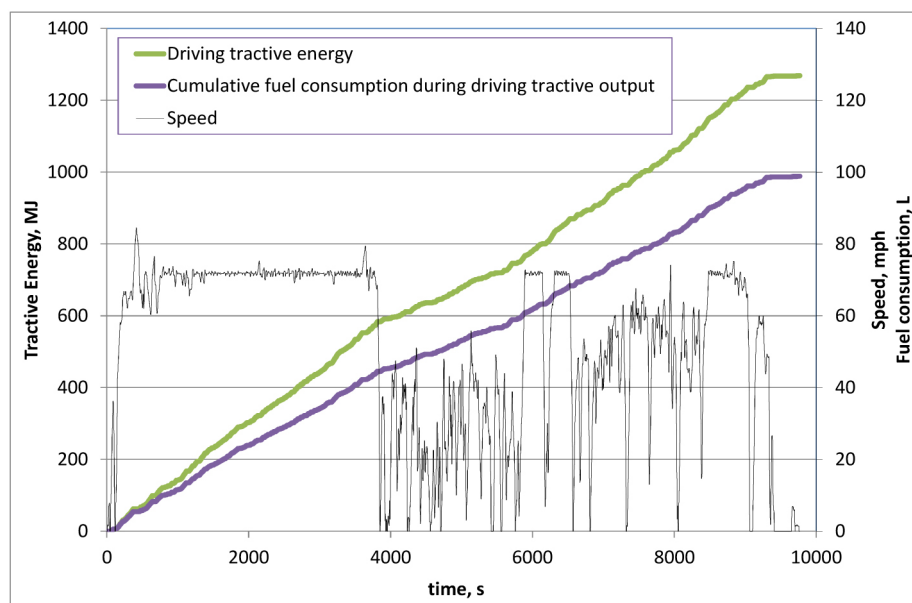


Figure 3. Comparison of tractive energy and cumulative fuel consumption during periods of positive tractive power during a measured drive cycle.

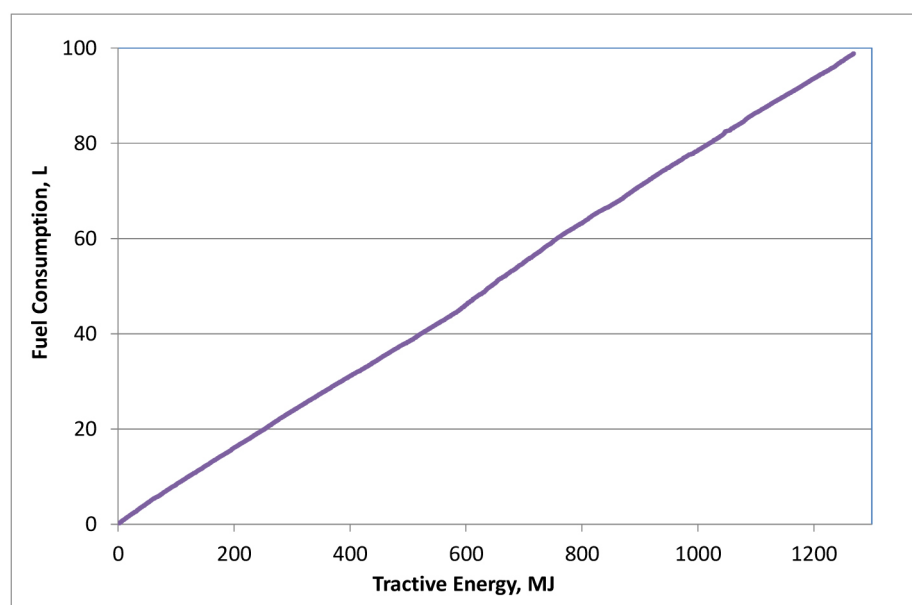


Figure 4. Cumulative fuel consumption during periods of tractive power output vs. tractive energy requirement

degree of linearity has been observed in all of the cases examined.

METHODS AND EQUATIONS

This section presents the equations that are used to quantify the energy savings potential of each technology individually, and the theoretical justification for the approach is described.

TRACTIVE ENERGY ANALYSIS AND FUEL SAVINGS POTENTIAL

The equations from the previous section can be used to estimate the fuel savings achievable if the driving tractive energy is reduced through the use of advanced vehicle efficiency technologies. Prediction of the total fuel economy is not expected to be extremely precise with this analysis since this will depend on a vehicle's specific configuration. However, estimating changes in fuel consumption with

different technologies is possible based on typical efficiencies, and relative comparisons between technologies should be reasonable using this approach. The fuel consumption associated with the tractive energy requirement is obtained by dividing the fuel energy by the heat of combustion. The lower heating value (LHV) is used for this purpose. Using [Eq. \(8\)](#), the result for the fuel consumption, $F_{c,}$ is the following:

$$F_{c,trac} = \frac{E_{fuel}}{LHV} = \frac{1}{\eta_{engine} LHV} \left(\frac{E_{trac}}{\eta_{trans}} + E_{acces} \right). \quad (10)$$

By analyzing the fuel consumption under different vehicle configurations for the same drive cycle, this equation can be used to estimate the fuel savings potential due to any changes in the tractive energy. The effect of changes to engine/transmission efficiency and accessory power can be evaluated at the same time. This approach allows one to estimate the fuel savings achievable with most advanced efficiency technologies, either individually or in combinations.

TECHNOLOGIES CONSIDERED AND CORRESPONDING EQUATIONS

The drive cycle and tractive energy analysis will be applied to evaluate the fuel savings potential for the following technologies: regenerative braking (hybrid vehicles), low rolling resistance tires, aerodynamic drag reduction devices, idle reduction systems, technologies that reduce vehicle mass, high efficiency drivelines (transmission, differential, etc.), and improved efficiency engines. These technologies have different characteristics that relate to the drive cycle and the tractive energy in different ways, and the analysis to determine the fuel savings potential for each is somewhat different depending on how the technology functions. Tire rolling resistance, aerodynamic drag, and regenerative braking all directly impact the tractive energy requirement through forces that they reduce. Mass of the vehicle and its payload also have a direct impact on the tractive energy requirement for a given drive cycle as a result of the vehicle inertia and gravitational forces, and mass also plays a strong role in the tire rolling resistance force. Since mass reduction affects the driving tractive energy through several forces simultaneously, its treatment for the tractive energy analysis is different than that for the other factors that influence individual forces associated with the tractive energy. Efficiency improvements of the engine itself and of the driveline reduce energy losses that are “upstream” of the tractive energy contributions. Therefore, the fuel savings associated with these technologies are approximately proportional to the driving tractive energy. Idle reduction technologies are not related to the tractive energy during driving, but a representative drive cycle, including periods of idle operation, is still important for being able to estimate the energy savings that are possible through idle reduction.

By accounting for all of the energy losses that affect fuel consumption over a drive cycle separately, the relative contribution from each can be determined. Knowing the contribution of each energy loss factor (rolling resistance, aerodynamic drag and braking) allows the fuel savings that a specified technology can provide to be estimated if the associated energy losses are known for each factor. By characterizing how much the energy losses associated with a fuel efficiency technology are reduced, the impact on the total tractive energy can be directly quantified. For example, if the contribution of tire rolling resistance is found to be 20% of the driving tractive energy requirement for a given drive cycle when the initial coefficient of rolling resistance is 8 kg/ton, then using low rolling resistance tires to obtain an average rolling resistance coefficient of 6 kg/ton (i.e. a 25% reduction) would be expected to reduce the tractive energy requirement by 5% (0.25 multiplied by 0.20). Based on [Eq. \(9\)](#), the fuel consumption during the driving periods of the drive cycle would be expected to improve by approximately the same percentage.

As discussed previously, the tractive energy contributions during periods of braking tractive force are not relevant to the fuel consumption for conventional vehicles, but for hybrid vehicles with regenerative braking, the energy that would otherwise be dissipated through the brakes can be recovered and used later. With regenerative braking, this recovered energy (or, accounting for inefficiencies, some portion of it) does reduce the driving tractive energy required from the engine during a later portion of the drive cycle when the previously stored energy is used to propel the vehicle instead of just the engine. Since the impact of driving tractive energy on fuel consumption does not depend on when the energy is required, we can evaluate the fuel savings potential of a hybrid vehicle by accounting for the energy losses that take place during the braking tractive power segments of a drive cycle. By accounting for the contributions to the braking tractive energy from each energy loss factor separately, we are also able to evaluate the fuel savings that can be achieved with combinations of the technologies including hybridization. Therefore, the contributions to both the driving and the braking tractive energy will be accounted for in each of the energy loss factors.

Before proceeding with the analysis, it is noted that coasting (defined as periods when the tractive force is zero) represents a special case with respect to the contributions of the energy loss factors to the driving tractive energy. Since the tractive force is zero during coasting, there is no change to the tractive energy during these periods. However, energy dissipation due to the tire rolling resistance and aerodynamic drag continue during coasting, so their contribution to the driving tractive energy can continue to accumulate even as the tractive energy does not change. The increase in the dissipated energy must be offset by a reduction in the combined kinetic and potential energy, as can be seen in [Eq. \(4\)](#) for periods of time when the net tractive energy does not change. To keep an accurate account of the driving tractive