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FUEL AND EMISSION IMPACTS OF HEAVY HYBRID VEHICLES

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ABSTRACT

Hybrid powertrains for certain heavy vehicles may improve fuel economy and reduce emissions. Of particular interest are commercial vehicles, typically in Classes 3-6, that travel in urban areas. Hybrid strategies and associated energy/emissions benefits for these classes of vehicles could be significantly different from those for passenger cars. A preliminary analysis has been conducted to investigate the energy and emissions performance of Class 3 and 6 medium-duty trucks and Class 6 school buses under eight different test cycles. Three elements are associated with this analysis: (1) establish baseline fuel consumption and emission scenarios from selected, representative baseline vehicles and driving schedules; (2) identify sources of energy inefficiency from baseline technology vehicles; and (3) assess maximum and practical potentials for energy savings and emissions reductions associated with heavy vehicle hybridization under real-world driving conditions. Our analysis excludes efficiency gains associated with such other measures as vehicle weight reduction and air resistance reduction, because such measures would also benefit conventional technology vehicles. Our research indicates that fuel economy and emission benefits of hybridization can be very sensitive to different test cycles. We conclude that, on the basis of present-day technology, the potential fuel economy gains average about 60-75% for Class 3 medium-duty trucks and 35% for Class 6 school buses. The fuel economy gains can be higher in the future, as hybrid technology continues to improve. The practical emissions reduction potentials associated with vehicle hybridization are significant as well.

INTRODUCTION

Numerous analyses, research and demonstration efforts, and tests have been conducted to help clarify the energy and emission benefits of hybridizing light-duty vehicles [1-4]. However, understanding of how hybridization will affect heavy-duty vehicles is limited, primarily because:

1. Unlike light-duty vehicles, heavy vehicles represent a much broader range of vehicle applications, resulting in a wide variety of vehicle chassis and engine combinations.
2. Because the applications are so varied, heavy vehicles also encounter more diverse driving conditions, which are much more difficult to characterize.
3. The Class 7-8 heavy-duty trucks that run on U.S. highways and dominate the trucking market in terms of sale and energy consumption overshadow the Class 3-6 commercial vehicles.

The hybridization of Class 7-8 highway trucks is less favorable in terms of energy savings. However, many demonstration projects exist around the world for hybrid urban transit buses. Transit buses are usually engaged in stop-and-go types of driving and are ideal candidates for

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hybridization. Many different design goals can be served by hybridizing conventional technology vehicles [1-2]; here, we are only interested in vehicle hybridization to maximize the overall vehicle fuel efficiency, as well as in the associated impacts on emissions.

ESTABLISH BASELINE FUEL CONSUMPTION AND EMISSION SCENARIOS

In the United States, Class 3-6 vehicles contribute relatively small shares (as percentage of heavy-duty vehicles, HDV) in terms of annual new vehicle sales, total vehicle miles of travel (VMT), and total energy consumption. Sales of new Class 3-6 vehicles amounted to about 28% in 1995. Their VMT share was about 19%, and their energy consumption share was about 13%. In 1995, most Class 3-6 vehicles still used gasoline engines (about 56%). Diesel engines are expected to increase market share, based on current trends [5]. These classes of vehicles usually serve as parcel delivery, utility/service, and tow/emergency trucks, as well as ambulance and shuttle buses, motor home chassis, and school buses. Motor home chassis and school buses are usually associated with the high end of gross vehicle weight rating (GVWR) classes (Class 6-7).

Select Representative Vehicles

Unlike light-duty vehicle manufacturers, heavy-duty vehicle manufacturers do not necessarily manufacture their own engines. Consequently, there is considerable flexibility in choosing different combinations of vehicle chassis and engines. In this analysis, we chose the following vehicle chassis and engine combinations as our baseline vehicles:

6. 1. A Class 3 Ford E-super duty chassis parcel delivery truck with a Navistar T444 E 7.3-L TDI diesel V8 engine;
7. 2. A Class 3 GMC C-Series P-chassis service delivery truck with a Vortec 5.7-L gasoline V8 engine; and
3. A Class 6 Navistar 300 Series school bus with a Navistar T466 E 7.7-L TDI Diesel V8 engine.

These combinations were selected because the vehicles are widely used and engine data are available.

Heavy-Duty Vehicle Driving Cycles

For light-duty vehicles, vehicle fuel consumption and emissions are extremely sensitive to different test cycles [3]. For heavy-duty vehicles, the dependence of fuel economy and emissions performance on test cycles can be even greater, mainly because heavy vehicles are used more diversely. Thus, it is critical to understand how heavy vehicles are driven under real-world conditions. We have identified eight existing test cycles for heavy-duty vehicles, as follows [6]:

1. CBD - Central Business District (CBD) cycle, as originally defined by SAE J1376.
2. NY-BUS - New York City Bus Cycle
3. NY-Truck - New York City Truck Cycle
4. NYGTC - New York City Garbage Truck Cycle
5. Truck-CBD - Truck CBD Cycle.
6. ART - Arterial Phase Truck Cycle
7. COMM - Commute Phase Truck Cycle
8. WVU5M – A West Virginia University research group developed this cycle in 1994.

Because these cycles have very diverse characteristics, they should provide useful insights for our study. Table 1 lists some characteristics of these eight heavy-duty vehicle test cycles.

Table 1 - Characteristics of Eight Truck Driving Cycles

Cycle	*Time, sec.*	*D, mi*	$<v>$, *mph*	v_{max}, *mph*	a_{max}, *mph/s*	K_{max}, *mph*^{2}*/s*	*Idle %*	*Acc, %*	*Dec, %*	*Cruise, %*
CBD	574	2.0	12.6	20.0	2.4	68.0	20.4	26.3	13.2	42.5
CBDtrk	854	2.2	9.2	20.0	0.8	24.0	18.6	50.5	26.0	6.6
NYbus	600	0.6	3.7	30.8	6.2	198.7	67.2	12.7	22.0	0.0
NYtrk	1016	2.1	7.6	34.0	4.4	221.0	52.0	24.0	20.5	5.5
NYGTC	585	0.4	2.3	20.0	3.0	65.5	69.2	11.3	11.3	9.7
WVU5M	900	5.7	22.8	39.9	5.0	395.0	17.9	3.9	12.9	65.9
ART	291	2.0	24.8	40.0	2.4	72.6	16.2	41.2	13.7	30.2
COMM	329	4.0	43.8	55.0	2.3	71.8	11.9	26.7	4.0	57.8
Average	644	2.4	15.8	32.5	3.3	139.6	34.2	24.6	15.5	27.3

In Table 1, the *Time* column gives the duration of the cycles in seconds, D is the length of each cycle in miles, $<v>$ is the average speed in miles per hour (mph), v_{max} is the maximum speed in mph, a_{max} is the maximum acceleration rate in mph/s, and K_{max} is the maximum specific energy K in mph^2/s. K, defined as twice the velocity times the acceleration rate, measures the rate of change of a vehicle's kinetic energy. Table 1 also gives the time-share of idling, acceleration, deceleration and cruise modes for these cycles. ART and COMM are the closest to freeway driving. CBD and CBDtrk are moderate urban cycles. NYbus, NYtrk, and NYGTC) are the most congested urban cycles.

Engine Map Approach for Emission Modeling

One of the simplest ways to model energy consumption and emissions for an internal combustion engine is based on measuring fuel consumption and emissions at steady-state loads and engine speeds, thereby creating so-called "engine maps". In our analysis, a brake-specific fuel consumption (*bsfc*) map and an NO_x emission map for the Navistar T444E diesel engine, based on steady-state engine emission tests conducted at Oak Ridge National Laboratory, were used. The biggest advantage of the engine map approach is its simplicity. The major disadvantage is that, being based on steady-state measurements, it may not accurately represent fuel consumption and emissions associated with transient events. Fortunately, with many HEV control strategies where the APU is operated at a fixed torque-rpm point (e.g., a "thermostatic" control strategy), transient emissions do not occur and so are not a major concern.

Baseline Vehicle Fuel Economy and Emissions

We have calculated the fuel economy and emissions for all three baseline vehicles under eight different driving cycles. As an example, Table 2 shows the fuel economy and emissions of the Ford E350 medium-duty truck under three different cycles. The results vary significantly from cycle to cycle; for instance, the modeled fuel economy ranges from about five miles per gallon (5 MPG) in the NY_Bus cycle to about 15 MPG in the COMM cycle. Great variations can occur in the vehicle's tailpipe emissions as well. Averaged over all eight cycles, this Class 3 diesel truck has a fuel economy of 9.6 MPG and CO, HC, NO_x, and CO_2 emissions of 0.74, 0.29, 12.6, and 849.2 g/mi, respectively.

Table 2 – Modeled Fuel Economy and Emissions of Ford E350

Cycle	*Fuel, MPG*	*CO, g/mi*	*HC, g/mi*	*NO$_x$, g/mi*	*CO$_2$, g/mi*
CBD_Truck	8.79	0.50	0.21	11.85	883.1
NY_Bus	5.31	1.50	0.57	19.24	1099.0
COMM	14.55	0.09	0.04	7.29	597.0
8-cycle average	9.56	0.74	0.29	12.58	849.2

Note: for HC and CO, 90% catalyst efficiency is assumed. Catalyst NO$_x$ efficiency is assumed to be zero.

ASSESS HEAVY-VEHICLE ENERGY INEFFICIENCY

In general, the energy inefficiencies of medium-duty trucks can be effectively assessed on the basis of the following three areas:

1. Energy loss associated with engine idling operation (when engine power demand ≤ 0).
2. Energy loss associated with vehicle braking (when engine power demand < 0).
3. Energy inefficiency associated with low engine part-load efficiency (when engine power > 0).

Fuel Consumption and Emissions during Engine Idling Mode

In the engine idling mode, vehicles are stopped or engaged in negative-power driving operation (or braking mode). Table 3 shows the time spent and energy and emission contributions from the medium-duty Ford truck during engine idling mode. The table shows a large variation in time spent, fuel consumption contributions, and emissions contributions during engine idling in these cycles. Averaged over the eight cycles, the engine idling mode contributes about 49% in time, 15% in fuel, 32% in CO, 49% in HC, and 15% in NO$_x$ emissions to the corresponding overall values.

Table 3 – Time, Energy, and Emissions Contributions of the Ford E350 Truck in Engine Idling Mode (%).

Cycle	*Time*	*Fuel*	*CO*	*HC*	*NO$_x$*
CBD_Truck	44.2	11.2	34.3	46.6	10.5
NY_Bus	86.4	33.2	55.4	84.3	31.6
COMM	15.9	1.5	14.0	20.8	1.3
Average	48.9	15.3	32.3	48.7	14.7

Of course, energy and emissions contributions during engine idling also vary with different vehicle/engine combinations. Table 4 shows the fuel consumption contribution during engine idling mode for three vehicle/engine combinations.

Table 4 - Fuel Consumption Contributions in Engine Idling Mode for Three Vehicle/Engine Combinations (%).

Cycle	*Time*	*Ford E350 Navistar TDI*	*GMC Vortec Gasoline V8*	*School Bus Navistar TDI*
CBD_Truck	44.2	11.2	22.3	6.6
NY_Bus	86.4	33.2	52.6	19.6
COMM	15.9	1.5	3.2	0.7
Average	48.9	15.3	25.7	9.3

Table 4 shows large variations in fuel consumption contributions among these vehicles under different test cycles. For the gasoline GMC truck, the idle fuel consumption contribution ranges from 3.2% in the COMM cycle to about 53% in the NY_bus cycle. For the diesel school bus, idle fuel consumption contribution ranges from less than 1% in the COMM cycle to about 20% in the NY_bus cycle. Averaged over the eight test cycles, the idle fuel consumption contribution of the gasoline GMC truck is the highest, near 26%, followed by the Ford truck with a Navistar diesel engine at 15% and by the Class 6 school bus at 9%.

Energy Losses associated with Vehicle Braking Operation Mode

For a given driving cycle, when vehicle power demand becomes negative, the vehicle's brake is applied. The cumulative negative power represents the total energy lost during vehicle braking. The cumulative engine positive power represents the total energy demand (or engine work) over a driving cycle by an engine, so the ratio of cumulative negative power over cumulative positive power is a measure of relative braking energy loss. Table 5 shows that the relative braking energy loss varies greatly from cycle to cycle, but not so much from vehicle to vehicle. Averaged over all cycles, the braking energy loss is about 32% of total engine work.

Table 5 - Ratios of Cumulative Negative Power over Cumulative Engine Work (%)

Cycle	*Negative Power Time*	*Ford E350 Navistar TDI*	*GMC Vortec Gasoline V8*	*School Bus Navistar TDI*
CBD_Truck	25.6	27.9	27.9	27.8
NY_Bus	19.2	53.8	53.8	54.1
COMM	4.0	12.1	12.1	11.5
Average	14.7	32.1	32.1	32.1

Heavy Vehicle Operating Efficiencies

We have used the following definitions to describe heavy-vehicle operating efficiency:

Peak Engine Efficiency, sometimes referred to as "peak brake thermal efficiency," is defined as engine indicated (or thermal) efficiency times engine maximum mechanical efficiency. For a gasoline engine, the indicated efficiency is about 38% and the maximum mechanical efficiency is about 85%; thus, gasoline engine peak efficiency is about 32%. For a conventional direct injection engine, the indicated efficiency is about 43% and the maximum mechanical efficiency is about 90%; thus, direct-injection engine peak efficiency is about 39%. For an advanced direct injection engine, indicated and peak efficiencies can reach 50% and 45%, respectively.

Engine Part-Load Efficiency, sometimes referred to as "relative engine mechanical efficiency," is defined as engine average efficiency during positive power driving over a test cycle, divided by the engine peak efficiency. Thus, engine part-load efficiency is a measure of the deficiency between the average engine efficiency and the peak engine efficiency.

Vehicle Transmission Efficiency is defined as cumulative power demand at the wheel, divided by cumulative power demand at the engine shaft (or battery terminal for EV or HEV cases). It is a measure of vehicle transmission loss.

Overall Vehicle Efficiency, the overall vehicle efficiency from drive wheel to fuel consumption, is the product of the three efficiencies defined above.

Table 6 indicates these efficiencies for the Ford E350 with the Navistar diesel engine, under the different cycles.

Table 6 - Ford E350 Operating Efficiency under Eight Different Cycles

Cycle	*Peak Engine Efficiency (a)*	*Part-Load Engine Efficiency (b)*	*Ave. Trans. Efficiency (c)*	*Overall Efficiency d=a*b*c*
CBD_Truck	39.3	69.6	53.5	14.6
NY_GTC	39.3	44.4	38.2	6.7
COMM	39.3	90.7	90.8	32.3
Average	39.3	69.9	66.4	19.0

The part-load engine efficiency varies greatly from cycle to cycle, ranging from as low as 44% in the NY_GTC cycle to as high as 91% in the COMM cycle. The average engine part-load efficiency over all cycles is about 70%. The transmission efficiency also varies greatly from cycle to cycle, ranging from 38% in the NY_GTC cycle to 91% in the COMM cycle. The average transmission efficiency over all cycles is about 66%. The variations associated with engine part-load efficiency and transmission efficiency result in even greater variation in overall vehicle efficiency, ranging from about 7% in the NY_GTC cycle to higher than 32% in the COMM cycle, almost a five-fold difference. The average overall vehicle efficiency is about 19%.

Engine peak, part-load, transmission, and vehicle overall efficiencies for all three vehicle/engine combinations, averaged over eight driving cycles, are given in Table 7.

Table 7 – Vehicle Operating Efficiencies for Three Vehicle/Engine Combinations
Averaged over Eight Driving Cycles (%)

Efficiency	*Ford E350 Navistar TDI*	*GMC Vortec Gasoline V8*	*School Bus Navistar TDI*
Peak engine	39.3	32.3	39.3
Part-load engine	69.9	60.6	81.9
Transmission	66.4	66.4	67.4
Overall	19.0	13.9	22.2

Table 7 shows that the peak engine efficiency for the Navistar diesel engines is about 39%, while that for the GMC Vortec gasoline engine is about 32%. The engine part-load efficiencies are about 70% for the Ford truck with the Navistar diesel engine, 61% for the gasoline GMC truck, and 82% for the school bus. The transmission efficiency is about 66% for the two Class 3 trucks and 67% for the school bus. The gasoline GMC truck has the lowest overall efficiency at about 14%. The Class 6 school bus has the highest overall efficiency at 22%. The Ford truck with the Navistar diesel engine has an overall efficiency of 19%.

ASSESS ENERGY SAVINGS AND EMISSIONS REDUCTION POTENTIALS

We assess the extent of energy savings and emissions reductions can be achievable by reducing or eliminating inefficient vehicle operating conditions. Two energy savings scenarios are used: (1) the maximum/ideal energy savings scenario, based on an ideal energy efficiency target; and (2) the practical energy savings scenario, based on today's technologies. Table 8 defines the two scenarios:

Table 8 – Energy Savings Scenarios for Hybrid Vehicles

Energy Savings Scenario	*Maximum/Ideal*	*Practical*
Idle Energy Use Reducible	100%	70%
Braking Energy Recoverable	100%	50%
Engine Part-Load Efficiency	100%	90%
Transmission Efficiency	100%	No change

The maximum/ideal scenario, which provides the upper limit of efficiency gain through heavy-vehicle hybridization, is discussed to show the relative effect of each of the component losses. The practical scenario, which reflects energy and emissions reductions in terms of today's technology, provides a more realistic picture of what we can expect from hybridizing heavy vehicles. In both scenarios, the efficiency gains associated with such measures as vehicle weight reduction and aerodynamic improvements are not considered, because such measures would also benefit conventional technology vehicles. We focus on benefits associated solely with hybridization.

Maximum/Ideal Energy Savings Potential

For the maximum/ideal energy savings scenario, we assume that all energy losses associated with engine idling operations can be eliminated, and that all energy losses associated with vehicle braking can be recovered through an "ideal" regenerative braking mechanism. Engine part-load efficiency can be improved to reach 100%, meaning that the engine can be operated at peak efficiency all the time, and there is no transmission loss over the entire course of the test cycle. Of course, this is a situation that can never be achieved. Table 8 summarizes this scenario.

We calculate the energy savings associated with each hypothetical assumption in Table 9, as well as the resulting fuel economy and MPG gain. Table 9 shows the energy saved from different operating modes for the Ford E350 Navistar Diesel TDI (7.3 L) under the maximum/ideal scenario.

Table 9 - Energy Saved for the Ford E350 under the Maximum/Ideal Energy Savings Scenario

	Energy Saved					*MPG*	
Cycle	Idle (%)	Regen. (%)	Trans. (%)	Part-Load (%)	Total (%)	New MPG	Gain (%)
CBD_Truck	11.2	27.9	41.2	20.0	73.5	33.2	277.6
NY_Bus	33.2	53.8	30.1	19.5	88.0	44.2	732.1
COMM	1.5	12.1	9.1	8.0	27.7	20.1	38.3
Average	15.3	32.1	26.5	20.4	68.5	34.4	350.9

In Table 9, the Idle column represents energy savings from eliminating engine idling operation, the Regen. column represents energy savings from recovering all braking energy losses, the Trans. column refers to energy savings from eliminating transmission losses, and the Part-Load column represents energy savings if the engine is operated at its peak efficiency all the time. The table shows that the energy savings from different modes differ by cycles. For instance, in the NY_Bus cycle, the greatest energy savings (54%) would come from recovering energy lost during vehicle braking. In the CBD_Truck cycle, the most energy (41%) would be saved by reducing transmission losses. Overall, vehicles driving in the NY_Bus cycle have the highest potential for energy savings, saving nearly 90% of total fuel use, which translates into a fuel economy gain of about 732%. Table 9 also shows that, averaged over all eight cycles, the largest energy savings potential is from recovering braking energy losses (32%), while the energy savings from transmission and part-load options are about 27% and 20%, respectively. Energy savings from the engine idle-off option is about 15%. The average overall energy savings is about 69%, which is equivalent to a fuel economy gain of 351%.

A similar analysis for the other vehicle/engine combinations under the maximum/ideal energy savings scenario was also done. Table 10 presents the fuel economy (MPG) gain for three vehicle/engine combinations under three individual test cycles, as well as the averaged gain over all eight cycles, for these vehicles. The averaged fuel economy gains (or multipliers) under the maximum/ideal energy savings scenario are about 351% (4.5) for the Ford E350, 482% (5.8) for the GMC truck, and 244% (3.4) for the school bus.

Table 10 – Fuel Economy (MPG) Gains under the Maximum/Ideal Energy Saving Scenario (%)

Cycle	*Ford E350 Navistar TDI*	*GMC Vortec Gasoline V8*	*School Bus Navistar TDI*
CBD_Truck	278	334	204
NY_Bus	732	1,033	537
COMM	38	38	34
Average	351	482	244
Multiplier (x)	4.5	5.8	3.4

Practical Energy Savings Potential

In this analysis, we focus only on the type of HEVs that aim at maximizing engine/vehicle operating efficiency and fuel economy. Although many development efforts are under way to manufacture hybrid Class 7-8 transit buses (as well as some urban delivery trucks developed by Volvo), few efforts are being made for Class 3-6 hybrid vehicles. Most hybrid transit buses under development are meant to achieve zero-emission mileage under urban driving conditions, akin to a pure-EV mode. This kind of hybrid bus is likely to be a series-configured hybrid vehicle with an on-board ICE operated at an optimal point; it is unlikely to be optimized for maximizing fuel efficiency.

Despite the variety of HEV design strategies, all hybrid vehicles have the following basic features: (1) turn off the engine during vehicle idling and deceleration modes, (2) incorporate some sort of regenerative braking mechanism, and (3) improve internal-combustion engine operating efficiency. Of course, added features for hybridization may impose penalties as well, such as added vehicle weight, energy loss associated with on-board battery charging, and a more complicated transmission system. Experience with today's light-duty HEVs shows that technical limits exist on how much wasted energy can be recovered in practice from the vehicle hybridization process. It is impractical to shut down an engine every single second when the vehicle is decelerating, for instance, especially during very brief decelerations that last only a few seconds. Technically, it is also impossible to recover 100% of braking energy; a more practical goal is about 50%, reflecting about 70% recovery efficiency from vehicle wheels and 70% efficiency in the transmission and charging process.

Designing a HEV to make the ICE operate at a single point is often called a "thermostatic" control strategy. However, it is more desirable in practice to operate the ICE over a range of power levels; within such a range, the ICE would follow the actual load demand of the vehicle. Such a strategy is often called "load following." For a load-following hybrid, one important step to improve the engine part-load efficiency is to significantly downsize the ICE and use a battery pack for supplemental power. The load-following strategy will not operate the ICE at its peak efficiency to achieve 100% part-load efficiency; rather, the ICE engine will operate over a "high-efficiency island" on the engine map, achieving roughly 90% part-load efficiency. More detailed discussion of hybridization issues can be found in Refs. 1-4.

We calculate the energy savings associated with hybridizing the Class 3-6 vehicles and associated new fuel economy and MPG gain. Table 11 shows the energy saved from different operational modes for the Ford E350 Navistar Diesel TDI (7.3 L) under the practical energy savings scenario.

Table 11 - Energy Saved for the Ford E350 under the Practical Energy Savings Scenario

	Energy Saved				*MPG*	
Cycle	Idle (%)	Regen. (%)	Part-load (%)	Total (%)	New MPG	Gain (%)
CBD_Truck	7.8	14.0	12.4	31.0	12.7	***44.9***

NY_Bus	23.2	26.9	14.3	51.6	11.0	***106.7***
COMM	1.1	6.1	(2.1)	5.0	15.3	***5.2***
Average	10.7	16.1	13.2	35.1	14.4	***61.1***

In Table 11, the Idle column represents energy saved from partially (70%) eliminating engine idling operation, the Regen. column represents energy saved from partially (50%) recovering braking energy loss, and the Part-Load column represents energy saved if the engine is operated at an average of 90% of its peak efficiency. As expected, the table shows that the energy savings from different options differ by cycles. Under the NY_Bus cycle, the greatest energy savings (27%, compared with about 54% in the ideal scenario) is still from recovering energy lost during vehicle braking. Vehicles driving in the NY_Bus cycles have the highest practical potential for energy savings, reaching 52%, which translates into a fuel economy gain of ~104%. Averaged over all eight cycles, the largest energy savings potential is from recovering braking energy losses (16%). , The energy savings from improving part-load efficiency and engine idle-off are about 13% and 11%, respectively. The average overall energy savings is about 35%, which is equivalent to a fuel economy gain of 61%.

Similar analyses for the other vehicle/engine combinations under the practical energy savings scenario were done as well. Table 12 presents the fuel economy (MPG) gain for vehicle/engine combinations under three individual test cycles and the averaged gain over all eight cycles. The averaged fuel economy gains (or multipliers) are about 61% (1.6) for the Ford E350, 75% (1.7) for the GMC truck, and 35% (1.3) for the school bus.

Table 12 – Fuel Economy (MPG) Gain for Vehicle/Engine Combinations under the Practical Energy Savings Scenario (%)

Cycle	*Ford E350 Navistar TDI*	*GMC Vortec Gasoline V8*	*School Bus Navistar TDI*
CBD_Truck	45	57	20
NY_Bus	107	127	79
COMM	5	4	2
Average	61	75	35
Multiplier (x)	1.6	1.7	1.3

Table 12 shows that the fuel economy gain associated with freeway driving cycle COMM is less than 5% for the first three vehicle/engine combinations. The biggest energy savings are from vehicles driving in stop-and-go urban traffic, such as the three New York City cycles. Under the NY-Bus cycle, the fuel economy gain from the diesel Ford truck with a Navistar engine is about 110%, that for the gasoline-fueled GMC truck is about 127%, and that for the school bus is about 79%.

Emissions Reduction Potential

Using similar methodology, the emissions reduction potentials associated with ideal and practical energy savings scenarios can be established. Table 13 presents the summary results for CO, HC, and NO_x emissions reduction potentials for three vehicle/engine combinations under the practical scenario, averaged over the eight test cycles. The practical emissions reduction potentials are about 30-42% for CO, 34-50% for HC, and 23-35% for NO_x.

Table 13 – Emission reduction potentials under the practical scenarios (%).

Compound	*Ford E350 Navistar TDI*	*GMC Vortec Gasoline V8*	*School Bus Navistar TDI*

CO	42	32	30
HC	48	34	43
NO_x	35	30	23

CONCLUSIONS

This paper assesses the potential energy savings and emissions reductions associated with hybridizing Class 3-6 medium-duty heavy vehicles. Fuel economy and emissions benefits of vehicle hybridization can be very sensitive to different test cycles. Based on today's technology, the potential fuel economy gains average about 60-75% for Class 3 medium-duty trucks and 35% for Class 6 school buses. The practical emissions reduction due to hybridization is also significant, about 30-42% for CO, 34-50% for HC, and 23-35% for NO_x. The ideal fuel economy gains and emissions reductions are much higher, implying that the benefits of vehicle hybridization will increase as hybrid technology continues to improve.

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