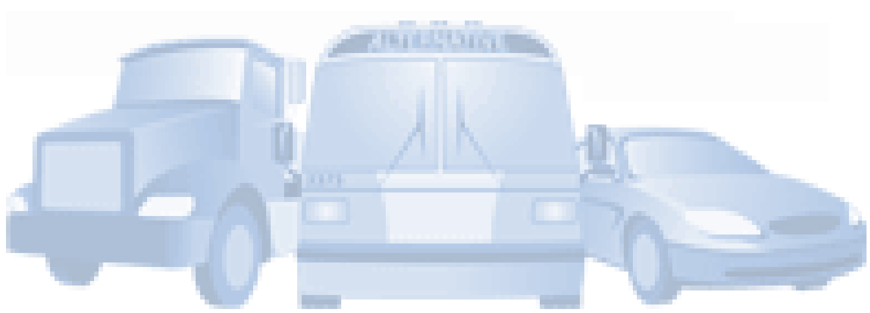
Mobile Source Emission Reduction In the NYMTC Region

Comparison of Hybrid, Plug-In Hybrid, Hydrogen and Clean Diesel Technologies



Date: 07/06/08

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Sponsored By:

NYMTC

Mobile Source Emission Reduction Planning
In the NYMTC Region

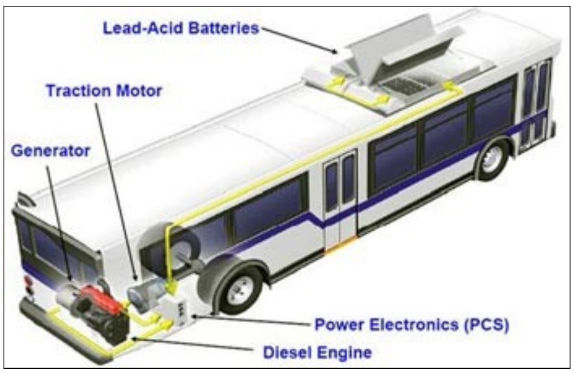
This research was part of a larger regional effort by NYMTC to reduce PM, NOx and CO2 from passenger cars, SUVs, buses and trucks. Nancy Mahadeo worked under supervision by Larry McAuliffe analyzing four mobile source emission reduction strategies— hybrid, plug-in hybrid, hydrogen and clean diesel technologies against conventional gasoline vehicles. It was found that plug-in hybrid electric vehicle technology was the most cost-effective strategy while hydrogen technology was too costly and clean diesel involved the production of higher NOx emissions.

Hybrid Vehicles

Introduction

Hybrids electric vehicles (HEVs) have already been used in the NYMTC region for the past decade. HEVs involve increasing the efficiency of gasoline or diesel vehicles. For the NYMTC region, this entails more miles of travel to the gallon and cheaper fuel costs. The Metropolitan Transportation Authority (MTA) and New York City Transit (NYCT) have used hybrid vehicles for a significant amount of their fleet and will add more hybrid vehicles in the near future.

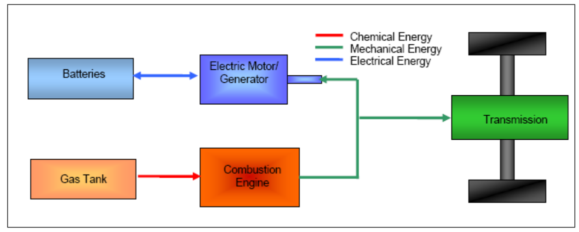
Figure 1—Hybrid Bus



Source:

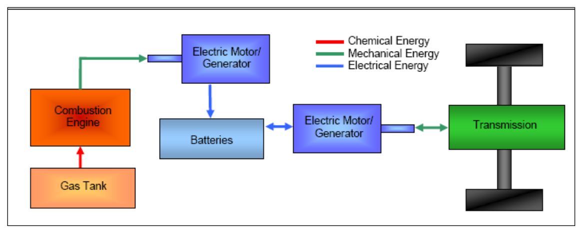
There are two main types of hybrids—parallel and series. Each is appropriate for different driving conditions. Parallel hybrids can be powered either through the battery or the internal combustion engine (ICE). After the depletion of the battery, they function like conventional hybrids recharging the battery during regenerative breaking. Freight, garbage and utility trucks are more appropriate for this type of design since they can take advantage of the engine off feature during idling. In the all-electric mode, series hybrids run off of the battery only. After the battery is drained, series plug-in hybrids contain the internal combustion engines (ICEs) that run continuously at optimal speed with the electric battery either being recharged with excess power or providing extra power for acceleration. Cars, SUVs and transit buses that encounter many stops and starts are more appropriate for this design since the internal combustion engine can cushion the drastic variations in energy load.

Figure 2 - Parallel Hybrid Electric Vehicle Schematic



Source: Pritchard, 2004

Figure 3 - Series Hybrid Electric Vehicle Schematic



Source: Pritchard, 2004

Fuel economy in hybrid electric vehicles is significantly higher than that of conventional vehicles as you can see below.

Table 1 - HEV Fuel Economy by Vehicle Type

	mpg	
	conventional	hybrid
Passenger car	24.1	37.1
SUV	18.5	28.5
Light Truck	13.0	19.9
Med Truck	9.9	15.2
Transit bus	3.6	5.4
School bus	7.2	8.1

Source: EPRI/NRDC Report, 2006

These achievements in higher fuel economy translate to lower emissions per mile.

Table 2-- Conventional Vehicle Emissions (grams/mile)

	mpg	CO2	PM	NOx
Passenger car	24.1	410	0.21	1.12
SUV	18.5	534	0.27	1.46
Light Truck	13.00	760	0.39	2.08
Med Truck	9.90	998	0.51	2.73
Transit bus	3.6	2783	1.43	7.60
School bus	7.2	1372	0.70	3.75

Source of mpg estimates: NRDC/EPRI, 2006
Source of emission reduction: EIA, 1998

Table 3 – HEV Emissions (grams/mile)

	mpg	CO2	PM	NOx
Passenger	37.1	266	0.14	0.73
SUV	28.5	347	0.18	0.95
Light Truck	19.9	497	0.25	1.36
Med Truck	15.2	650	0.33	1.78
Transit bus	5.4	1830	0.94	5.00
School bus	8.1	1220	0.62	3.33

Source of mpg estimates: NRDC/EPRI, 2006
Source of emission reduction: EIA, 1998

Table 4 – HEV Emissions *Reduction* (grams/mile)

	CO2	PM	NOx
Passenger	144	0.07	0.39
SUV	187	0.10	0.51
Light Truck	264	0.13	0.72
Med Truck	348	0.18	0.95
Transit bus	954	0.49	2.60
School bus	152	0.08	0.42

Table 4 above shows the reductions of emissions per mile hybrids incur as compared to conventional vehicles.

Below are estimates of transit buses, cars and SUVs in each area in the NYMTC region. Table 5 and 6 show the emission reduction from hybrids currently or soon to be implemented and the potential emission reduction if all said vehicles were hybrid.

Table 5 - Emissions Reduction from Transit Buses in NYMTC Region (Tons per Year)

Area	# of Cars/SUVs	# Hybrids	Annual Vehicle Miles Traveled	Reduction with Incoming Hybrids (tons/year)			Reduction if All Vehicles Hybrid (tons/year)		
				CO2	PM	NOx	CO2	PM	NOx
NYC	3,209,968	96,299	13,000	198,251	102	542	6,608,377	3,385	18,052
Westchester	351,428	10,543	13,000	21,705	11	59	723,487	371	2,578
Rockland	96,968	2,909	13,000	5,989	3	16	199,628	102	1,000
Putnam	35,269	1,058	13,000	2,178	1	6	72,607	37	480
Nassau	441,888	13,257	13,000	27,292	14	75	909,717	466	16,494
Suffolk	489,383	14,681	13,000	30,225	15	83	1,007,495	516	2,921

Source of number of fleet vehicles: 2006 National Transit Database
Source of number of new hybrids: http://www.mta.info/nyct/facts/ffbus.htm ,

Table 6 - Emissions Reduction from Passenger Cars and SUVs in NYMTC Region in 2010 (Tons per Year)

Area	# of Buses	# Hybrids	Annual Vehicle Miles Traveled	Reduction (tons/year)			Reduction if All Vehicles Hybrid (tons/year)		
				CO2	PM	NOx	CO2	PM	NOx
NYC	5735	850	40,000	35,738	18.3	97.6	241,124	123.5	658.7
Westchester	407	95	40,000	3,994	2.0	1.7	17,112	8.8	46.7
Rockland	66	45	40,000	1,892	1.0	0.0	2,775	1.4	7.6
Putnam	14	10	40,000	420	0.2	0.0	589	0.3	1.6
Nassau	355	0	40,000	0	0.0	0.0	14,926	7.6	40.8
Suffolk	0	0	40,000	0	0.0	0.0	0	0.0	0.0

Source of number of total vehicles : U.S. Census, Cornell PAD Projections
Assumption: hybrids make up 3% of all passenger cars and SUVs

Area	# of Trucks	# Hybrids	Annual Vehicle Miles Traveled	Reduction with Incoming Hybrids (tons/year)			Reduction if All Vehicles Hybrid (tons/year)		
				CO2	PM	NOx	CO2	PM	NOx
NYC			2,300,000				882	0.45	2.4
Long Island			1,500,000				575	0.81	1.6
Hudson Valley			4,700,000				1,803	0.40	4.9

Costs

In order to determine the cost-effectiveness

	Conventional		Hybrid	
	mpg	$/mi	mpg	$/mi
Passenger car	24.1	0.17	37.1	0.11
SUV	18.5	0.23	28.5	0.15
Med Truck	9.9	0.49	15.2	0.32
Transit bus	3.6	1.38	5.4	0.91
School bus	7.2	0.68	8.1	0.60

Assumption: gasoline price $4.20/gal, diesel price $4.90/gal

of HEV technology, these emissions need to be compared to lifecycle costs which primarily depend upon the purchase cost and fuel cost. The chart below depicts the cost of travel in a HEV as compared to a conventional vehicle.

	Premium Cost ($)	Annual Vehicle Miles	Savings ($/yr)	Years to Payback
Passenger car	$6,860	13,000	$794	8.6
SUV	$6,040	13,000	$1,036	5.8
Med Truck	$30,000	40,000	$6,903	4.3
Transit bus	$80,000	40,000	$18,915	4.2
School bus	$80,000	40,000	$3,025	26.4

Source of passenger car price:
http://www.fueleconomy.gov/feg/hybrid_sbs.shtml
http://automobiles.honda.com/civic-hybrid/
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http://www.carsdirect.com/research/compareresults?acodes=USB80NIC111A0,USB80NIC041A0
Souce of truck price:
Source of transit bus price: Chandler, 2006
Source of school bus price: Randall, 2006
Source of VMT: FHWA, 2007;
National Transit Database, 2006
Assumption: gasoline price $4.20/gal, diesel price $4.90/gal

Recovery time depends upon the differences in capital costs because as that premium since it determines the savings/year. If gas prices were to double from $3.50 to $7.00, then the savings/year would double across vehicle classes and the number of years to payback would lessen. The vehicle miles of travel (VMT) also effect recovery time. The savings/year in Figure 4 assumes 14,600 miles of travel/year (40 miles/day) for passenger cars and SUVs all in the electric mode. Trucks and buses are assumed to travel the same per day in electric mode and an additional 40,000mi/year. As VMT increases, the savings/year will also increase.
HEVs are definitely ready for implementation right now in the NYMTC region. As for heavy-duty applications, trucks and transit buses have a reasonable long recovery period in which lower fuel costs make up for the higher capital costs. However, recovery period still appears to be too long for school buses since the higher mpg incurred by hybrid technology isn't enough to make up for the higher purchase cost. Therefore, trucks and transit buses are ready for implementation but school buses are not given current fuel costs.

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Plug-In Hybrid Electric Vehicles

Introduction

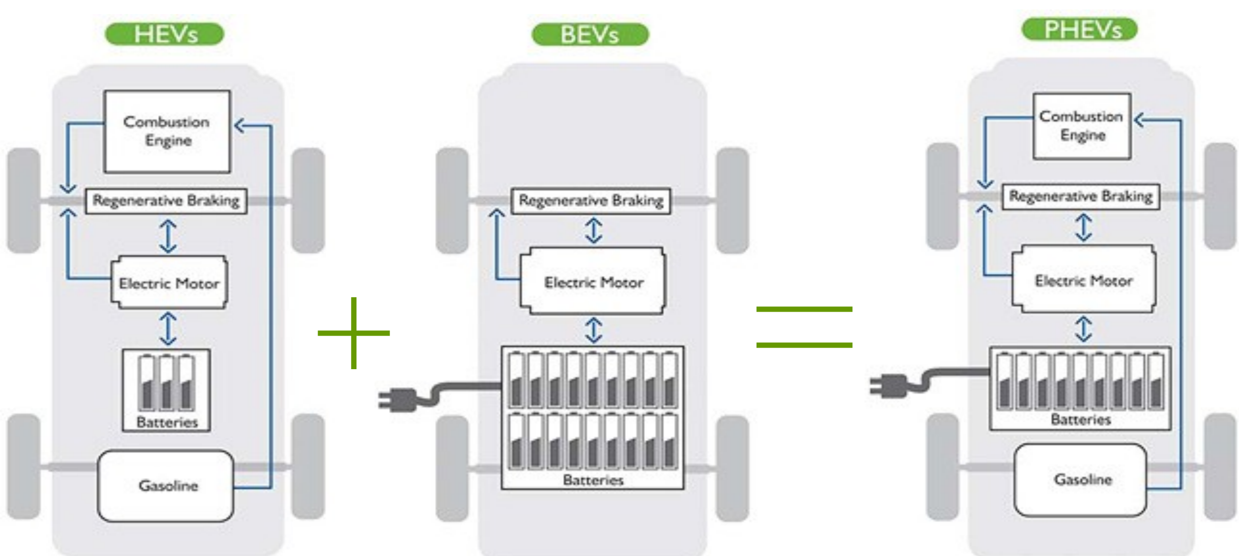
Plug-in hybrids electric vehicles (PHEVs) may be the most promising strategy for mobile source emission reduction in the NYMTC region. Since the U.S. average roundtrip urban commute travel distance is about 40 miles and many plug-in hybrids can go 40 miles on electricity alone, they have the potential to provide urban commute travel without the use of gasoline. For the NYMTC region, this implies overall reduction in emissions since NY State electricity is produced from a mix of natural gas, nuclear power, hydropower and coal which is cleaner than gasoline.

PHEVs combine aspects of both hybrid electric and electric vehicles. PHEVs have two driving modes–electric mode and hybrid electric mode. The electric mode involves using an electric battery as the only means to power the vehicle and is referred to as "charge depleting" mode. In the all-electric range, the batteries are drained but can be recharged with a connection to an 110V electric outlet without the use of gasoline or diesel.

PHEVs also have the flexibility of functioning like a typical hybrid vehicle if no electricity is available for recharge. In this case, gasoline or diesel would run the vehicle with the batteries being recharged through regenerative breaking. This mode is referred to as "charge sustaining". In addition to the flexibility of fuel between gas and electricity, PHEVs are also flexible in size. They are modular in design such that components can be added together to vary from the scale of a passenger car to as big as a tractor trailer fairly easily.

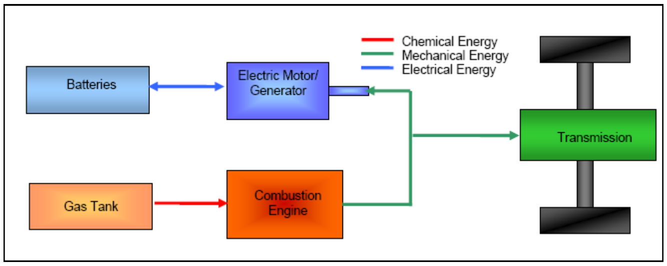
There are two main types of plug-in hybrids—parallel and series. Each is appropriate for different driving conditions. Parallel plug-in hybrids can be powered either through the battery or the internal combustion engine (ICE). After the depletion of the battery, parallel hybrids function like conventional hybrids recharging the battery through regenerative breaking. Freight, garbage and utility trucks are more appropriate for this type of design since they can take advantage of the engine off feature during idling. Vehicles that are mostly used for highway driving are also appropriate for parallel hybrid design. As for series plug-in

Figure 1—Plug-In Hybrid Electric Vehicle Design



Source: http://www.burbankwaterandpower.com/phev.html#3

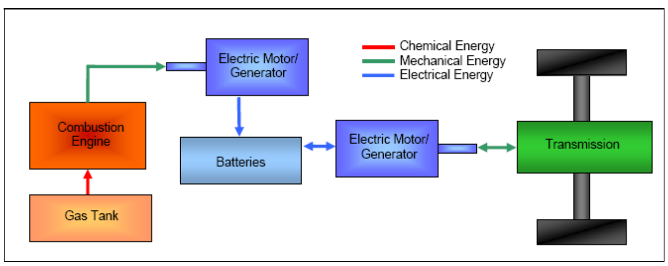
Figure 2 - Parallel Hybrid Electric Vehicle Schematic



Source: Pritchard, 2004

hybrids, the wheels of the vehicle are powered directly from the battery only. After the battery is drained, an internal combustion engine (ICE) runs continuously at optimal speed with the electric battery either being recharged with excess power from the ICE or the electric battery providing extra power for acceleration. Cars, SUVs and transit

Figure 3 - Series Hybrid Electric Vehicle Schematic



Source: Pritchard, 2004

buses that encounter many stops and starts are more appropriate for this design since the internal combustion engine can cushion the drastic variations in energy load.

Fuel economy reporting for plug-in hybrids has been a bit awkward because the period of time in the electric-only phase is usually included. For instance, plug-in hybrids may report a fuel economy of 77 mpg that includes 40 miles driven with electricity and 37 miles driven in hybrid electric-gas mode on 1 gallon of gasoline. This means that:

$(40 \text{ miles})_{\text{electric}} + (37 \text{ miles})_{1 \text{ gal gas}} = 77$ miles per 1 gallon = 77 mpg

But…

$(40 \text{ miles})_{\text{electric}} + (37 \text{ miles})_{1 \text{ gal gas}} + (37 \text{ miles})_{1 \text{ gal gas}} = 114$ miles per 2 gallons = 57 mpg

The more miles driven in hybrid mode, the less accurate the stated fuel economy becomes. To avoid this ambiguity, this analysis involves separating fuel economy between hybrid and all-electric mode as shown in the 3rd and 4th columns below.

Table 1 – Fuel Economy by Vehicle

	Conventional	PHEV Electric	PHEV Hybrid Mode
	(mpg)	(mpgge)	(mpg)
Passenger Car	24.1	120.3	37.1
SUV	18.5	97.1	28.5
Truck	9.9	45.4	15.2
Transit Bus	3.6	33.7	4.6
School Bus	7.2	40.8	8.1

Source: EPRI/NRDC, 2006; Pritchard, 2004; Diesel Hybrid Webinar
Note: mpgge means miles per gallon gas equivalent

Table 2 – Emissions for Conventional Vehicles (grams/mile)

	mpg	CO2	PM	NOx
Passenger car	24.10	370	0.19	1.01
SUV	18.50	482	0.25	1.32
Truck	5.30	1864	0.86	4.59
Transit bus	3.60	2745	1.27	6.76
School bus	7.20	1372	0.63	3.38

Source: EPRI/NRDC, 2006; Pritchard, 2004; Diesel Hybrid Webinar

Table 3 – Emissions Grams per Mile for PHEVs in Electric Mode

	mpgge	Watt-hr/mi	CO2	PM	NOx
Passenger car	120.3	280	100	0.16	0.13
SUV	97.1	347	124	0.20	0.16
Truck	45.4	743	265	0.43	0.33
Transit bus	33.7	1000	357	0.58	0.45
School bus	40.8	825	294	0.48	0.37

Source: EPRI/NRDC, 2006; Pritchard, 2004; Diesel Hybrid Webinar

These achievements in higher fuel economy translate to lower emissions per mile as shown below.

Table 4 – Emissions Grams per Mile for PHEVs in Hybrid Mode

	mpg	CO2	PM	NOx
Passenger car	37.1	240	0.12	0.66
SUV	28.5	313	0.16	0.85
Truck	15.2	650	0.33	1.78
Transit bus	4.6	2148	1.10	5.87
School bus	20.0	494	0.25	1.35

Source: EPRI/NRDC, 2006; Pritchard, 2004; Diesel Hybrid Webinar

Table 5 – Percent Emissions Reductions for PHEV as Compared to Conventional Vehicle Emissions

	Electric Mode (grams/mile)			Hybrid Mode (grams/mile)		
	CO2	PM	NOx	CO2	PM	NOx
Passenger car	73%	14%	88%	35%	35%	35%
SUV	74%	18%	88%	35%	35%	35%
Truck	86%	50%	93%	65%	61%	61%
Transit bus	87%	54%	93%	22%	13%	13%
School bus	79%	24%	89%	64%	60%	60%

Assumptions: ratio of emissions from electric mode for each CO2, PM, and NOx constant across all vehicle categories

Table 6 - Fuel Costs by Vehicle Class Conventional vs. PHEV

	Conventional	PHEV Electric Mode	PHEV Hybrid Mode
	$/mi	$/mi	$/mi
Passenger car	0.17	0.04	0.11
SUV	0.23	0.05	0.15
Truck	0.49	0.10	0.32
Transit bus	1.36	0.14	1.07
School bus	0.68	0.12	0.25

Source: EPRI/NRDC, 2006
Assumption: gasoline price of $4.20/gal, diesel price $4.90/gal, 0.14 cents/watt electricity

Table 5 shows the reductions of emissions per mile plug-in hybrids incur as compared to conventional vehicles. As you can see, electric mode emissions reduction is greater than that of hybrid mode since electricity in NY State is powered by a mix of natural gas, nuclear power, hydropower and coal which is cleaner than gasoline.

Costs

In order to determine the cost-effectiveness of PHEV technology, these emissions need to be compared to lifecycle costs which primarily depend upon the purchase cost and fuel cost. The chart below depicts the cost of fuel in a PHEV as compared to a conventional vehicle. The 1st column shows the fuel costs in a conventional vehicle, while the 2nd and 3rd columns show the fuel costs for a PHEV in all-electric and hybrid modes.

As you can see, PHEVs involve a much lower cost of travel per mile in either electric or hybrid modes. Despite these advantages, PHEVs have not undergone mass production due to long period of time it takes to recapture the capital costs and a few other problems.

Table 7 - Recovery Payback Time

	Premium Cost	Miles Per Year	Savings/ year	Years to Payback
Passenger car	$15,000	14,600	$1,972	7.6
SUV	$15,000	14,600	$2,605	5.8
Truck	$88,000	40,000	$10,091	8.7
Transit bus	$88,000	40,000	$25,344	3.5
School bus	$100,000	40,000	$19,313	5.2

Source of car/SUV price: fueleconomy.gov
Source of truck price: NREL, year
Source of transit bus prices: Odyne newsletter
Source of school bus price: NYSERDA
Assumption: gasoline price of $4.20/gal, diesel price $4.90/gal, 0.14 cents/watt electricity
Assumption: all PHEVs have all-electric range of 40 miles.

Recovery time for recuperating capital costs varies among different vehicle classes. As you can see in Figure 4 above, passenger cars and SUVs require about 7.6 and 5.8 years respectively in order for the higher fuel economy to offset the premium price for plug-in technology. Since trucks and buses involve a drastically higher amount of vehicle miles of travel, their recovery times are much shorter ranging from 3.5 to 5 years.

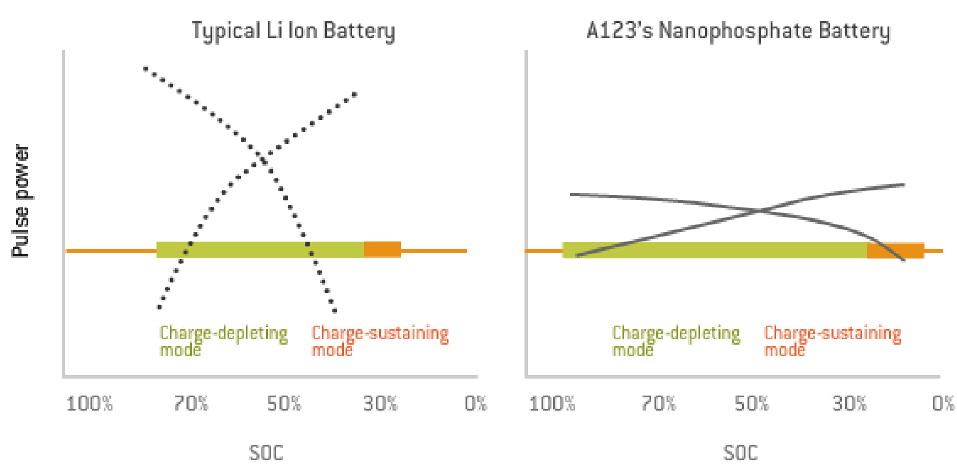
Recovery time primarily depends on capital cost premium, fuel prices, number of miles traveled. The capital cost premium depends upon the difference in capital cost between conventional vehicles and plug-in vehicles. As that difference shrinks, the number of years to recover the difference will also decrease. Gasoline and diesel prices also affect recovery time since it determines the monetary savings per year. If gas prices were to double from $3.50 to $7.00, then the savings per year would double across vehicle classes and the number of years to payback would decrease by half. The vehicle miles of travel (VMT) also effect recovery time. The savings per year in Figure 4 assumes 14,600 miles of travel/year (40 miles/day) for passenger cars and SUVs all in the electric mode. Trucks are assumed to travel about 275 miles per day with the first 40 miles each day in all-electric mode. Transit and school buses are assumed to travel about 110 miles per day with the first 40 miles also in all-electric mode. As the vehicle miles per day increases, the savings per year will also increase.

PHEVs have had the following challenges in mass market implementation: cost, battery size/weight, durability and safety. A123 Systems have made great advancements in this area. With the use of nanotechnology and lithium ion technology, an A123 battery stores two times the energy as a typical lithium ion battery used in current hybrid electric vehicles. Also these improved batteries allow bursts of power similar to that seen in conventional vehicles.

As you can see in the diagram above, their battery technology have allowed for flatter discharge curves meaning that it takes a longer time to fully discharge while supplying the same amount of energy at any given instant. Unlike conventional lithium-ion batteries, which use a cobalt-oxide material that can overheat and cause laptops and cell phones to burst into flame, A123's batteries use a much more stable, and potentially cheaper, iron phosphate material. Durability and safety can be further shown through testing and there are several pilot programs happening right now within the NYMTC region.

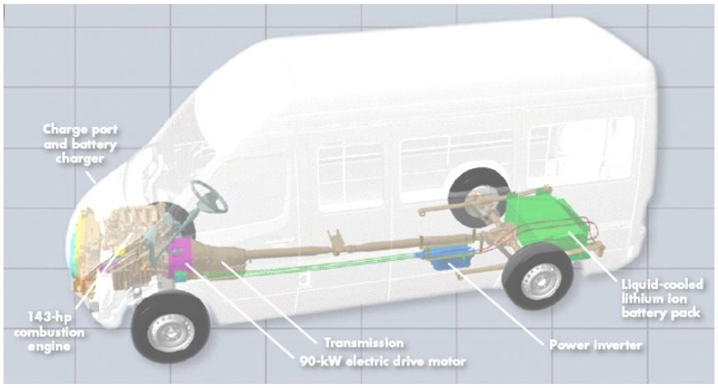
In New York City, the NYTimes is using several Dodge Sprinter plug-in vans in their delivery fleet. They are being used as deliv-

Figure 4 – How A123 Systems' Batteries Work



Source:http://www.a123systems.com/newsite/index.php#/applications/phev/pchart3/

Figure 5—Sprinter Plug-In Delivery Van



Source: online

ery vans from College Point, Queens to their Manhattan headquarters. Long Island also has PHEV pilots happening. In Hempstead and Long Beach, each town is taking on two plug-in hybrid garbage trucks in their sanitation fleets. These are being retrofitted with lead acid batteries. Huntington bought two 32-ft plug-in hybrid transit buses and one plug-in refuse truck. And finally the Town of Oyster Bay is converting three recycling trucks to PHEVs.

Many experts say that if pilot programs go well, mass production of PHEVs of all vehicle classes may be occurring within 5 years. As for passenger cars, Toyota has announced recently that a plug-in version of the Prius Hybrid sedan will be available in 2010 for sale first only to big commercial customers like corporations and government fleets and then later to the general public. GM also has plans for a plug-in passenger car, the Chevy Volt Concept. Also, Ford is coming out with a plug-in version of the Escape for 2012. As for trucks and buses, there are no current plans for near-term mass production. However the Long Island-based Odyne Corporation, which specializes in alternative technology for heavy-duty vehicles, has been retrofitting truck and bus fleets with plug-in technology on a case-by-case basis. They have worked with NYSERDA on all the PHEV pilot projects mentioned above.

As mass production occurs, PHEVs will yield cheaper components so that the overall vehicle capital cost premiums will decrease significantly. This means that as PHEVs take a larger proportion of the vehicle market, the time it takes to recover the capital cost premium will decrease drastically. Also as mentioned before, increases in fuel prices will also make PHEVs cheaper in the long-run.

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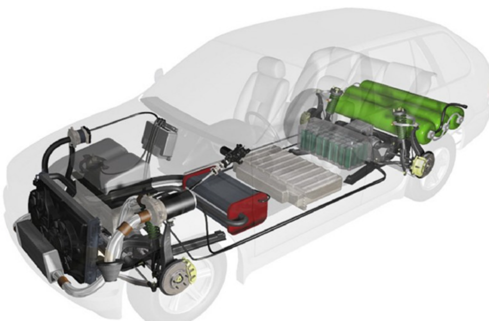
Hydrogen Fuel Cell Vehicles

Introduction

Hydrogen fuel cell vehicle technology has been hyped as having the potential to reduce vehicle emissions to zero. However, hydrogen technology is quite far from being ready for implementation in the NYMTC region. The single most important barrier to implementation is cost while other barriers and safety.

Figure 1 - Hydrogen Fuel Cell Car



Source: online

Hydrogen fuel cells use compressed hydrogen from the hydrogen tank and oxygen from the turbo compressor to create elec-

production and the efficiencies of each stage of hydrogen after production as shown in Figure 2 and 3 below.

The chart below shows the grams of pollutants emitted for the production phase. As you can see, hydrogen produced from natural gas and electrolysis yield different orders of magnitude of emissions.

Table 1 - Emissions from the Production of Hydrogen

Emissions from H2 Production		
	Natural Gas	Electrolysis
	g/kg H2	g/kg H2
CO2	8,889	19,102
PM	0.022	31.12
NOx	0.898	23.99

Hy-

Note: g/kg H2 means grams of emissions per kilogram of hydrogen produced
Source: EIA, 1998

Hydrogen production can be done on a large-scale, offsite or it can be done on a small scale on-site in the fueling station. Currently, 95% of all hydrogen produced in the U.S. is done in large scale facilities using natural gas and is trucked into hydrogen

Figure 2 - Hydrogen Journey to Your Vehicle Through the Natural Gas Process

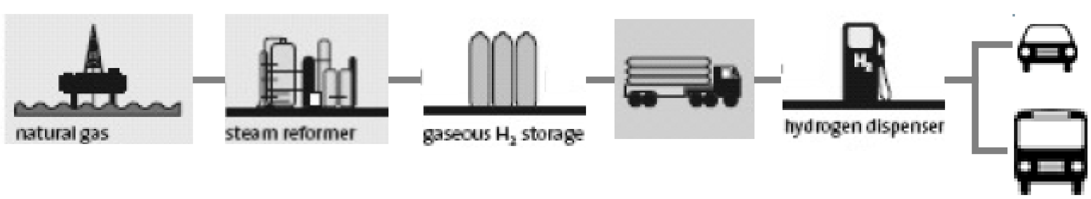
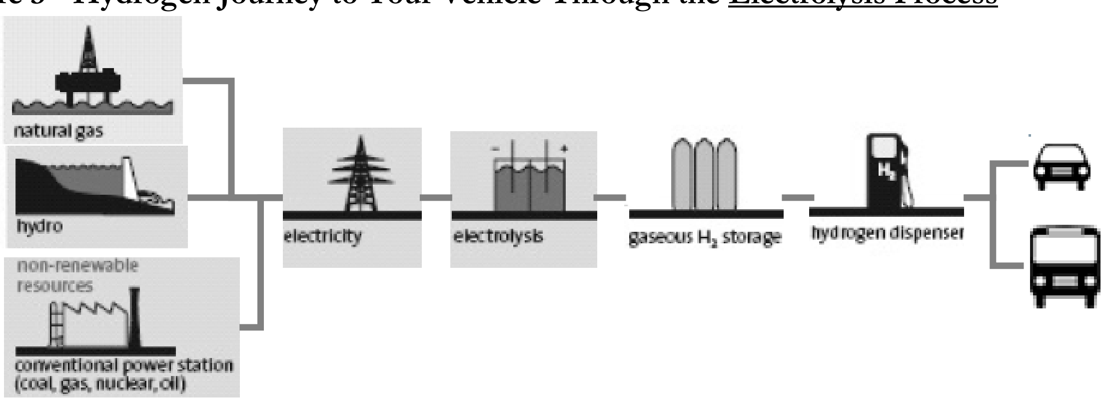


Figure 3 - Hydrogen Journey to Your Vehicle Through the Electrolysis Process



fueling stations. The truck emissions would have a direct effect on air quality in the NYMTC region.

If hydrogen production is done onsite then emissions may take the form of point sources within or outside the NYMTC region. Hydrogen production through natural gas steam reforming onsite would entail point source emissions. If electrolysis is used instead there would be no emissions in the NYMTC region directly but there might be emissions related to electricity generation. The chart below depicts the sources of New York State electricity.

Table 2 - New York State Electricity Sources

natural gas	30
nuclear	30
hydroelectric	19
coal	14
petroleum	5
renewables	2

Source: EIA, 2006

As you can see, only 2% of the electricity in NYState comes from renewable sources of energy like wind and solar power. In order to bring down the emissions from electricity by increasing the renewables share, there would be high capital costs for the construction of wind and solar electricity plants.

Currently, there is one hydrogen fueling station in the NYMTC region located off the I287 in White Plains that uses electrolysis. Other stations in the NYMTC region may have to truck in hydrogen from this site or may produce hydrogen onsite of their own.

Once hydrogen is produced it must be stored securely otherwise it will be lost to the air. Unlike other transportation fuels, hydrogen must be stored at very high pressure. Both gas and liquid forms of hydrogen are highly energy intensive but liquid storage requires even more energy since it must be kept at a very low temperature. Both gas and liquid storage of hydrogen significantly decreases the energy efficiency of hydrogen use. Below are efficiencies of transporting hydrogen from the point of production to the point of use. As for onsite hydrogen production, the distribution efficiency loss may not be as significant since there would be no travel distance.

Table 3 - Efficiency of Different Stages of Hydrogen Gas Use

Packaging	Storage	Distribution	Transfer	Total Loss
8%	0.50%	6%	1%	16%

Source: Bossel, 2003
Assumption: packaging at 200 bar pressure
Assumption: distribution at 200 bar and distance of 60 miles
Assumption: liquid storage
Assumption: transfer 200 bar to 200 bar

This loss of efficiency translates to an even higher emissions per unit kilogram produced as shown below.

Table 4 - Emissions from H2 Production Given Efficiency Losses

Emissions from H2 Production		
	Natural Gas	Electrolysis
	g/kg H2	g/kg H2
CO2	10312	22158
PM	0.026	36.10
NOx	1.042	27.83

Note: combined data from Table 1 and Table 3
Note: g/kg H2 means grams of emissions per kilogram of hydrogen produced

The chart above shows the emissions per unit hydrogen up until the point of use in the vehicle. The emission per mile depends upon the fuel economy. A kilogram of hydrogen is equivalent in energy content to 1.12 gallons of gasoline. The fuel economy for a hydrogen vehicle is denoted below by gge – gallon gasoline equivalent. This measure is helpful when comparing hydrogen vehicles to conventional vehicles.

Table 5 - Fuel Economy and Emissions (grams/mile

A. Conventional Vehicles

	mpg	CO2	PM	NOx
Passenger car	24.10	370	0.19	1.01
SUV	18.50	482	0.25	1.32
Transit bus	3.60	2745	1.27	6.76

B. Hydrogen – Natural Gas

	mpgge	CO2	PM	NOx
passenger car	61.9	166	0.000	0.017
SUV	43.5	237	0.001	0.024
transit bus	6.1	1692	0.004	0.171

C. Hydrogen – Electrolysis

	mpgge	CO2	PM	NOx
passenger car	61.9	358	0.583	0.45
SUV	43.5	510	0.640	0.64
transit bus	6.1	3636	0.000	4.57

Source: article
Note: mpg means miles per gallon, mpgge means miles per gallon gas equivalent of hydrogen (1 kilogram of hydrogen equals 1.12 gallons of gasoline)

These differences in fuel economy translate to reductions of emissions per mile. However, using vehicles with hydrogen produced from electrolysis appears to yield higher CO2 and PM emissions per mile as denoted below in bold.

Table 6 - Emission Reduction Per Mile – Natural Gas vs. Electrolysis

A. Hydrogen – Natural Gas

	CO2	PM	NOx
	grams/mile		
Passenger car	-55.0%	-99.8%	-98.3%
SUV	-50.8%	-99.8%	-98.2%
Transit bus	-38.3%	-99.7%	-97.5%

B. Hydrogen – Electrolysis

	CO2	PM	NOx
	grams/mile		
Passenger car	-3.3%	207.6%	-55.5%
SUV	5.8%	159.5%	-51.3%
Transit bus	32.5%	-100.0%	-32.5%

Costs

In order to determine the cost-effectiveness of hydrogen vehicle technology, these emissions need to be compared to lifecycle costs which primarily depend upon the purchase cost and fuel cost. The chart below depicts the cost of travel in a hydrogen vehicle as compared to a conventional vehicle.

Table 7 - Comparing Costs of Travel – Gasoline Vehicles vs. Hydrogen Vehicles

	Conventional		Hydrogen - Natural Gas		Hydrogen - Electrolysis	
	mpg	$/mile	mpgge	$/mile	mpgge	$/mile
Passenger car	24.10	0.17	61.9	0.06	61.9	0.28
SUV	18.50	0.23	43.5	0.08	43.5	0.41
Transit bus	3.60	1.36	6.1	0.60	6.1	2.90

Assumption: $4.20/gal for gasoline, $4.90/gal for diesel, $3.68/kg H2 (from natural gas), $17.65/kg H2 (from electrolysis)

In general, hydrogen vehicle purchase costs are astronomical as compared to other vehicle technologies. Hydrogen vehicles can typically be five times higher than conventional vehicles even when cost savings for high-volume manufacturing are applied. As you can see below, higher purchase prices alone result in absurdly long payback periods across all vehicle classes.

Table 8 - Recovery Payback Time With Hydrogen from Natural Gas

	Premium Cost	Savings/year	Years to Payback
Passenger car	$75,000	$1,677	45
SUV	$165,000	$2,078	79
Transit bus	$1,050,000	$30,287	35

Assumption: 14,600 mi/year U.S. average for passenger car and SUV

Capital costs not only involve the purchase of vehicles but the installment of hydrogen fueling stations and the possible installment of hydrogen production facilities. The construction of a natural gas fueling station would add $10.8 million to capital costs and an electrolysis fueling station would add about the same at $11.4 million.

This premium in lifetime cost of hydrogen fuel cell vehicles is a significant impediment to widespread implementation. The only way these comparative costs will be reduced is either through significant breakthrough in technology that reduces capital costs or higher gasoline and diesel prices that will increase the savings/year.

Complications

CASE STUDY – European Union

Hydrogen fuel cell vehicles, in addition to being expensive, are also very complicated and therefore more prone to component failures and off-road repair time. In the Clean Urban Transport for Europe (CUTE) study, ten cities across Europe each added three hydrogen fuel cell buses to their transit fleets and created unique systems of hydrogen production and infrastructure. Hydrogen was produced through electrolysis on a small scale, onsite in Amsterdam, Barcelona, Hamburg, Stockholm and Reykjavík. Each site used a combination of one or more of the following sources for electricity – oil, natural gas, wind, solar, hydropower, etc. Hydrogen was produced through small scale, on-site natural gas steam reforming in Madrid and Stuttgart. Luxembourg, Porto and London trucked in hydrogen from large -scale, off-site producers. For the latter half of the study, London shipped in liquid hydrogen instead of gas hydrogen.

According to the study, the energy effi-

ciency of hydrogen production and dispensing was quite poor. Also, the following problems were found:

- Repeated corrosion and breakage of fueling station nozzles which were due to contact with the high pressure hydrogen gas.
- Two instances of contamination of the hydrogen gas which meant months off the grid for cleaning
- Repeated failures of converting fuel cell electricity to power to the wheels
- Repeated failures of sensors used to detect dangers such as the leaking of hydrogen or the contamination of stored hydrogen

In general, all sites consistently experienced one or more of the problems listed above. For the entire period of 22 months, Reykjavík had no data to report because of complications with hydrogen production through electrolysis. Madrid experienced a similar problem with data reporting since they had data for only 4 out of the 22 months because of complications with the onsite hydrogen production from natural gas.

As for safety, training hydrogen bus operators is important since hydrogen is colorless and odorless but can be ignited easily. Training in the CUTE study was done through emergency response drills rather than training manuals. Emergency response drills involved trained staff to directly apply knowledge to solve problems. Bus drivers did not have to be trained of highly technical information since manufacturer technicians were present during training and application. Staff training was assumed to be easier if recruitment was on voluntary basis.

CASE STUDY – Arizona

Another pilot study of hydrogen vehicles was conducted in Arizona from January 2006 through November 2006. For about half of the study, the fuel cell bus was only available for 61% of the time. This was generally due to air conditioning that caused problems with the fuel cell system.
Some complications that arose included difficulties with the air conditioning system in high temperatures (110-120° F) which led to other failures in the vehicle drive system. Also, contaminants were released from a fuel cell stack due to problems with component materials.

Other Problems

There are other problems with fuel cell vehicles that were not addressed in the studies in Europe or Arizona which include long-term durability, variations in humidity, and proton exchange membrane (PEM) durability. If hydrogen vehicles are to compete with conventional vehicles, they need to withstand 5,000 hours or more of heavy load operation in the long-term. Currently hydrogen vehicles have been found to have as much as 1000 hours of life. Also, hydrogen vehicles cannot withstand variations in humidity levels which degrade the fuel cells. A part of the fuel cell called the PEM can be severely challenged by variations in power demanded in the automotive driving cycle. This leads to chemical and physical stresses in the PEM and result in tears or pin-holes and membrane failure, well before the 5000 h target lifetime.

HHICEs are a good stepping stone to HFCVs because they are not as complicated and therefore not as prone to system failure. HHICEs are much simpler, similar to a conventional vehicle with an internal combustion engine. They perform in all weather conditions, all temperatures, require no warm-up, and get a fuel economy similar to HFCVs. However, hydrogen tanks take up much more space than gasoline tanks since hydrogen has much lower energy density. This still results in a much lower driving range than a conventional car which is the biggest hurdle. Advancements in higher density storage technology are estimated to arrive in a few decades.

Conclusion

Although, there are a few hydrogen refueling stations planned in the NYMTC region, one in White Plains as previously mentioned and another in Hempstead, LI, there are too many problems for widespread use. In general, mass production of hydrogen vehicles within 5 or 10 years is highly unlikely due to the technical problems and high capital costs. Technological advancements that would allow hydrogen vehicles to be cheaper and/or simpler are estimated to take 20 years or more.

Hydrogen vehicles may be cost competitive with gasoline vehicles if gasoline and fuel prices rise. In order to recover the capital costs of hydrogen vehicles within five years of operation, gasoline prices would have to increase drastically as shown below.

Table 9 - Hydrogen Competitive Gasoline Prices – 5 Year Payback Period

Since gasoline and diesel prices are not expected to reach these levels in the short – term, hydrogen may never be cost effective enough for implementation in the NYMTC region within 5 or 10 years.

vehicle class	$/gallon
Passenger car	$26
SUV	$43
Transit Bus	$20

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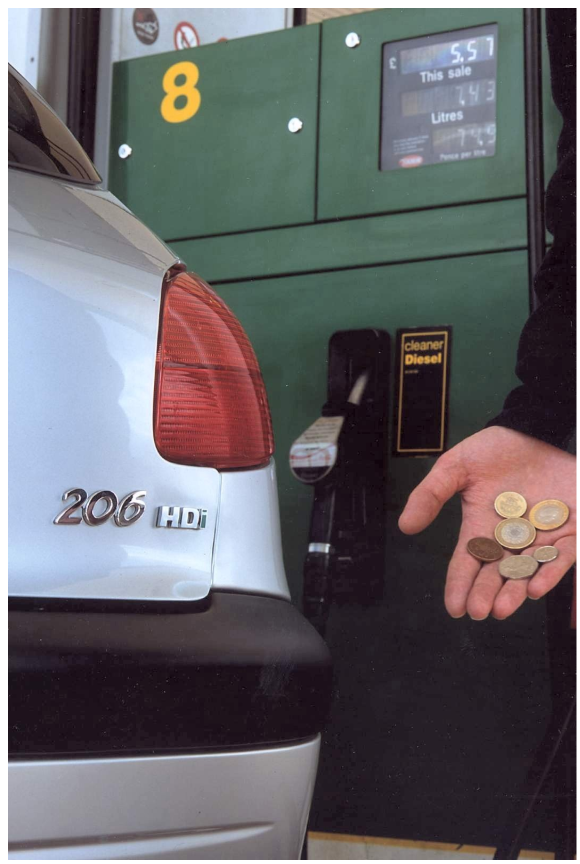
Clean Diesel Cars and SUVs



Introduction

Clean diesel technology has been used as an emission reduction strategy in light-duty vehicles in Europe for the past decade. There has been much hype about introducing diesel cars in the U.S. in the next 20 years due to higher fuel economy and cost-effectiveness as compared to conventional gasoline vehicles.

Diesel vehicles have some advantages over conventional gasoline vehicles. First, diesel fuel has more torque and more energy content per volume than gasoline fuel. In a vehicle, this translates to 20-40% greater efficiency than gasoline. Second, diesel vehicles have emissions control devices that can lower PM and NOx.

Fuel economy relates to emissions since it determines the efficiency of travel. The figure below shows the fuel economy for typical gasoline cars and SUVs and their clean diesel counterparts.

Evidence for diesel fuel economy has been conflicting. According to the U.S. DOE's fuel economy website, light-duty ULSD vehicles appear to have higher fuel economies than their diesel counterparts. The National Renewable Energy Laboratory did a study in March 2007 on diesel SUVs and found that during the first 200 hours of testing, fuel economy at 15 mpg and during the following 1800 hours fuel economy increased to 15.4 mpg.

In addition to higher fuel economy, emission control devices are also a means to reduce per mile emissions of PM, NOx and CO2. However, these emissions control devices typically cannot work to reduce all pollutants equally. Some may reduce one pollutant while increasing emissions of another. Some of these devices have been listed below:

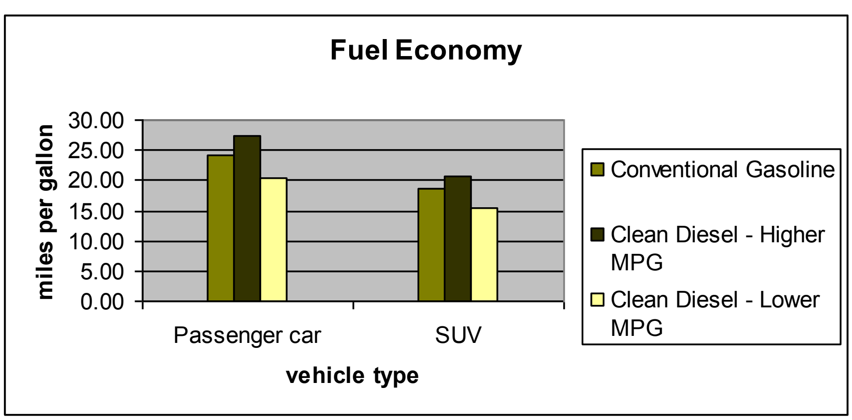
Table 1 – Clean Diesel Emission Reduction

	PM	NOx
ultra-low sulfur diesel	5-10%	n/a
diesel particulate filter	up to 90%	n/a
diesel oxidation catalyst	20-50%	n/a
lean NOx trap	up to 90%	25%
exhaust recirculation	up to 90%	50%
exhaust recirculation with DPF	up to 90%	60-90%
selective catalytic reduction	30-50%	up to 90%

Source: EPA Progress Report 2005 http://www.dieselforum.org/meet-clean-diesel/what-is-clean-diesel/

One or more of these devices can be used to have a significant impact on PM and NOx but each individual device may have a lesser effect as shown above. The use of ultra-low sulfur diesel (ULSD) is the current

Figure 1 – Fuel Economy



Source: fueleconomy.gov and NREL, 2005

standard for all diesel fuel in the U.S. and can have an immediate impact of a 10% reduction in PM emissions. Diesel particulate filters (DPFs), lean NOx traps, and exhaust recirculation systems tend to have a significant effect on PM emissions each capable of a reduction up to 90%. The only devices that have similar impact on NOx emissions are the combination of exhaust recirculation systems with DPFs and selective catalytic reduction systems.

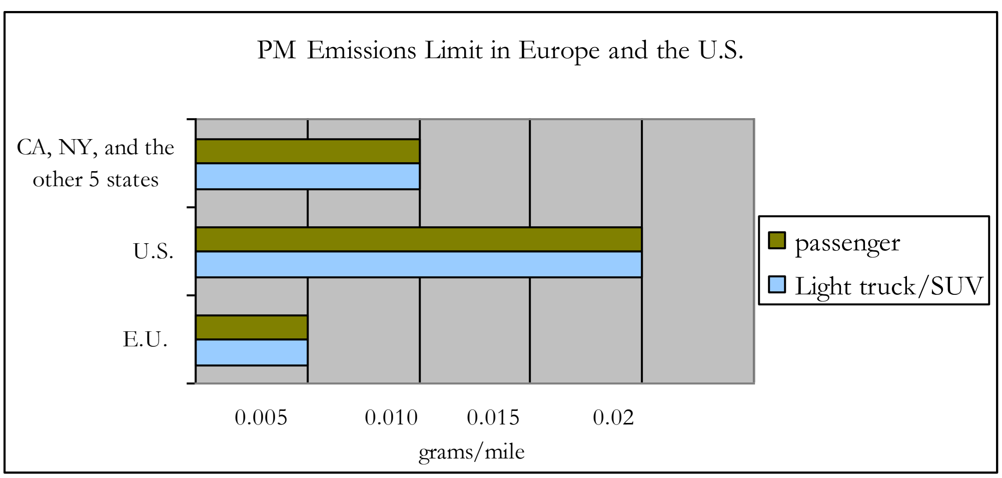
Clean diesel fuel in combination with emission control devices can reduce PM and NOx by as much as 90% than traditional diesel vehicles. The following charts compare conventional gasoline vehicles with clean diesel vehicles that may have higher fuel economy and lower fuel economy. Also, emission limits are shown for E.U. standards and U.S. federal standards. U.S. vehicle emissions standards in contrast, have the same standards for diesel and gasoline vehicles and for passenger and light-trucks. Federal emissions standards are stricter on PM and NOx emissions but have no re strictions on CO2 emissions. Automakers have been able to get their fleet's average emissions adhere to Bin 5. However, New York as well as six other states have even stricter emissions standards and therefore do not have any light-duty diesels available for sale. As you can see below, clean diesel technology has been able to get PM down almost to the level of U.S. and E.U. emission standards.

A vehicle manufacturers light duty fleet must have average emissions like that of Bin 5 – 0.05 grams/mile of NOx and 0.01 grams/mile of PM. and. Diesel light duty vehicles are not allowed in New York State because New York has adopted California standards which are even stricter than federal standards. As part of the California LEV program, none of the vehicles in an automakers fleet can emit more emissions per mile of NOx and PM than that prescribed by Bin 5 of the federal limits.

With the ULSD and emission control devices, PM emissions are much lower with clean diesel vehicles whether they get slightly higher or lower fuel economy. However, they do not seem to achieve the EU emission limit 0.005 grams/mile or the U.S. limit of 0.01 grams/mile for 2009. However, federal standards for PM are met for all cases of diesel light duty vehicles except SUVs with low fuel economy as shown in Table 7. four times more emissions per mile of PM.

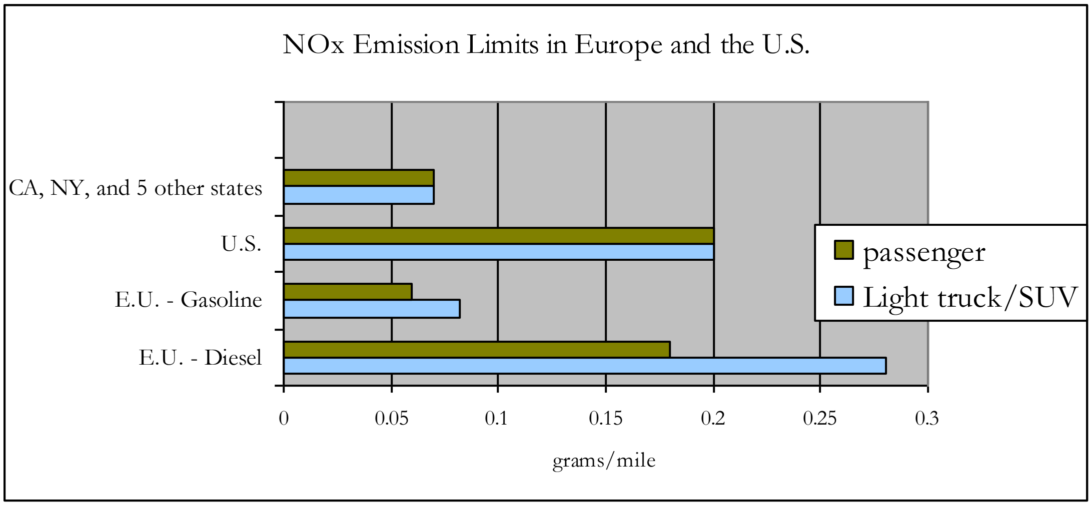
However, NOx has been proven to be too difficult and costly to bring down to gasoline level in the

Figure 2 - PM Emissions Limits for Europe and the U.S.



Source: http://www.edmunds.com/ownership/techcenter/articles/123901/page001, http://www.dieselnet.com/standards/eu/ld.php#stds

Figure 3 - PM Emissions Limits for Europe and the U.S.



Source: http://www.edmunds.com/ownership/techcenter/articles/123901/page001, http://www.dieselnet.com/standards/eu/ld.php#stds

near future. Therefore, the E.U. has set a much higher limit for diesels than that of gasoline vehicles.

As you can see above, diesel vehicles are allowed to emit about 0.18 grams/mile of NOx while gasoline vehicles are only allowed to emit about 0.06. The U.S. has chosen to use the higher 0.20 grams/mile limit as well for NOx. Because of the more lax standards for diesel vehicles, the EU has been able to encourage diesel light-duty vehicles so that they make up half of all light-duty vehicles. As you can see in Table 6 and Table 7, the federal emissions standards for NOx are not met in any case for diesel light duty vehicles. As you can see, the EU allows eight times more emissions per mile of NOx.

CO2 emissions are the focus of E.U. emissions standards. The EU signed the Kyoto Protocol in 1997 promising to reduce greenhouse gas emissions (GHGs) by 8% below 1990 levels by 2012. Now in Europe, diesel vehicles account for more than half of the light-duty vehicle market even though they experience higher emissions of NOx. Diesel vehicles have been used as a quick strategy to achieve their GHG goals.

In general, the E.U. has adjusted its standards for NOx emissions from light duty vehicles to accommodate diesel technology and lower CO2 emissions.. In the U.S. and especially states like California and New York, diesel technology will never be used in the foreseeable future since they will not be relaxing NOx vehicle emission standards.

Costs

Even if New York were to make NOx emission standards accommodating for diesel light duty vehicles, the lower fuel costs cannot help to recover the higher capital costs in a reasonable amount of time.. Diesel fuel costs, as shown below, clean seems to achieve only a 2 cents reduction per mile due to the slightly higher fuel economy.

Table 2 - Fuel Costs in Light Duty Vehicles, Gasoline vs. Clean Diesel

	Conventional Gasoline		Clean Diesel	
	mpg	$/mi	mpg	$/mi
Passenger car	24.1	0.15	27.5	0.13
SUV	18.5	0.19	20.8	0.17

This savings per mile translate to a yearly savings that is not significant enough to balance the higher purchase cost. As you can see below, the premium for passenger cars and SUVs are in the tens of thousands. With the yearly savings, the payback period in which the higher capital costs can be recovered is much too high as shown in Table 10 below.

Table 3 - Recovery Time from Higher Diesel Purchase Cost

	Premium Cost ($)	Savings ($/yr)	Years to Payback
Passenger car	$17,100	262	65.2
SUV	$10,425	300	34.8

Looking to the Future

If diesels were to make up a higher share of all light-duty vehicles in the U.S., then they would become more common which would reduce capital costs. However, diesels are not foreseen as penetrating the car and SUV market anytime soon. Cambridge Systematics, Inc. (CSI) has done a study on the possible penetration of diesel vehicles in the U.S. light duty fleet and found that 14 % of all light trucks and 10% of all cars can be diesel powered by 2010 with levels like that in Europe possible by 2020.

Currently several car companies have been making diesel cars and SUVs available in the U.S. However, none can be purchased or registered in the State of New York because they do not meet emissions standards. The automakers listed in Table 11 claim that they will meet those standards by the production dates listed.

Figure 4 - Mercedes 320 Bluetec

In general, light duty diesel vehicles are not ready right now for implementation in the NYMTC region since they are not allowed in New York State. In the next 5 years, there may be light duty diesel vehicles that meet emission standards but the capital costs may see an increase due to more devices needed for PM and NOx emissions. This may result in capital cost recovery times that are even longer than shown in Table 10. Therefore, due to high costs light-duty diesel vehicles will not be ready within 5 or 10 years in the NYMTC region.

Table 4 – Light Duty Diesel Vehicles Planned For Near Future

Manufacturer	Vehicle Model	Expected Date
Acura	TSX	2009
Audi	A4 Sedan	2009
Audi	Q7 3.0 TDI SUV	2009
BMW	X5 xDrive 35d	Fall 2008
Ford	F-150 Light Truck	2010
Cadillac	CTS Sedan	2010
Chevrolet	Silverado	2009
HUMMER	H2 SUV	2010
Hyundai	Veracruz SUV	2009
Kia	Borrego SUV	2011
Mercedes-Benz	E320 Bluetec	2009
Saturn	Aura Sedan	2010
Volkswagen	Bluetec	May-08
Volkswagen	Toureg	Summer 2008
Volkswagen	Sportswagen	Dec-08
Volkswagen	Tiguan SUV	July-08
Volkswagen	Passat	July-08

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