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Energy, Greenhouse Gas, and Economic Implications of Natural Gas Trucks

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Abstract

Until recently, natural gas was an also-ran in the sweepstakes for changing the face of transportation in the United States, even though expanded reliance on natural gas vehicles (NGVs) holds the promise of reducing carbon emissions, reducing dependence on oil, and even lowering transportation costs. Recently, however, interest in natural gas as a transportation fuel has grown, as shale gas resources expanded and people became more interested in finding ways to reduce greenhouse gas (GHG) emissions.

The purpose of this paper is to investigate the evidence for and against natural gas vehicles as a reasonable option to their closest alternatives, focusing primarily on heavy-duty natural gas (LNG) trucks compared to diesel trucks.

This investigation is based on a literature review that covers energy use and GHG emissions and then two simulation analyses. The first simulation examines how various assumptions about investment costs, fuel price differentials, fuel economy, miles driven, discount rate, etc., can alter the private (as opposed to social) economic case for substituting new natural gas vehicles for their diesel-fueled counterparts. The second examines the case for natural gas trucks from the perspective of social welfare by estimating their social costs relative to diesel trucks and their cost-effectiveness with respect to oil and GHG reductions within the modeling framework of the National Energy Modeling System (NEMS), as modified by RFF into NEMS–RFF . Because the NEMS model (the 2009 version, including the stimulus package and a four year advance of new CAFE requirements to 2016) only incorporates NGVs by assumption, rather than through economic decisionmaking, we assume a given penetration rate of new vehicles into the fleet over the model’s horizon of 2030. We then track the effects of this penetration on GHG emissions, oil use, and other variables to make offline estimates of the social welfare costs, under various assumptions. As a final analysis, we run the NEMS–RFF model with enhanced gas shale resources taken from estimates from the Potential Gas Committee (PGC) (see Brown, Krupnick, and Walls 2009 for details).

We conclude that LNG trucks can, under certain conditions, be a good deal for society in reducing oil and CO₂ emissions with reasonably competitive cost-effectiveness, even without government subsidies or mandates. We also conclude that infrastructure issues may be less of a challenge than commonly thought because the interstate trucking industry is moving increasingly from a long-haul route structure to a “hub and spoke” structure—a development which could facilitate more judicious placement of LNG refueling stations and therefore make use of LNG trucks more prevalent.

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Alan Krupnick*

Introduction

Natural gas vehicles (NGVs) have been a part of global vehicle fleets for decades, with an estimated 11 million on the road today worldwide.¹ The United States ranks 12th globally in number of NGVs on the road, which is considerably behind countries such as Argentina, Brazil, Italy, and India.² Our estimated 110,000 NG vehicles³ represent a small fraction of the more than 250 million vehicles on the road in the United States.

Until recently, natural gas was an also-ran in the sweepstakes for changing the face of transportation in the United States, even though expanded reliance on NGVs holds the promise of reducing carbon emissions, reducing dependence on oil, and even lowering transportation costs.

Recently, however, interest in natural gas has grown,⁴ as vast new resources have become available and interest in finding ways to reduce greenhouse gas (GHG) and smog-forming emissions has increased. A study undertaken by the Department of Energy's National Renewable Energy Laboratory and UPS showed that when compared to diesel truck emissions, trucks running on natural gas 7 percent lower carbon dioxide (CO₂) emissions (Chandler et al. 2002). A more recent study by the California Air Resources Board shows reductions in CO₂ emissions of 20 percent or more.⁵ Reducing oil use follows directly from substituting natural gas for diesel. Assuming the same mileage in diesel equivalent terms, a truck traveling 100,000 miles per year with fuel economy of five miles per gallon (mpg) uses 20,000 gallons per year.

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¹ http://www.ngvc.org/about_ngv/index.html

² <http://www.anga.us/2010/01/gm-embraces-natural-gas-in-light-duty-pickups/>

³ <http://www.detnews.com/article/20090709/AUTO01/907090403/Bill-would-boost-natural-gas-vehicles?imw=Y>

⁴ Among the prominent supporters of expanded use of natural gas vehicles is energy businessman T. Boone Pickens, who introduced a plan in 2007 to use wind power to generate electricity, thus "freeing" natural gas for use in vehicles.

⁵ Although natural gas once enjoyed a decided advantage in emissions of conventional pollutants, that advantage is gone in 2010 as engines using diesel or other fuels must meet strict standards for particulate matter (PM), non-methane hydrocarbons (NMHC), and nitrogen dioxide (NO_x) and refineries must produce very low sulfur diesel fuel.

Natural gas vehicles are also included in new government policies. In August 2009, the Department of Energy announced that funding for natural gas technologies and fueling stations would be included in a \$300 million grant under the American Recovery and Reinvestment Act (PL 111–5). In addition, the Energy Tax Policy Act of 2005 (PL 109–58) provides an income tax credit for the purchase of a new, dedicated alternative fuel vehicle of up to 50 percent of the incremental cost of the vehicle, plus an additional 30 percent if the vehicle meets certain tighter emission standards. These credits would range from \$2,500 to \$32,000 depending on the size of the vehicle. The credit is effective on purchases made after December 31, 2005 and expires on December 31, 2010⁶.

Yet even proponents of natural gas concede that these vehicles face significant obstacles to capturing a major share of the market. Irrespective of the vehicle type, there are concerns regarding economics—the equivalent gasoline or diesel vehicle is cheaper, although fuel costs are likely to be higher—as well as concerns about safety and availability of refueling stations. The latter is the “chicken and egg” problem: vehicle users will not buy NGVs until they believe there are enough refueling stations, but there is little motivation to build an NGV refueling infrastructure until a sufficient number of vehicle owners demand the fuel. There are other concerns as well. The cruising range and cabin space of light-duty vehicles may be insufficient. Heavy-duty trucks may also have inadequate range unless they are fueled by liquefied natural gas (LNG). Intermediate weight trucks, buses and refuse trucks already use natural gas in significant numbers, but represent a relatively small market.

We investigate the evidence for and against natural gas vehicles as a reasonable option to their closest alternatives, focusing primarily on heavy-duty long-haul natural gas trucks compared to diesel trucks. In this paper, we examine the use of vehicles that are powered by compressed natural gas (CNG), natural gas in its gaseous state that is compressed by high pressure, or liquefied natural gas (LNG), natural gas that has been cooled and condensed into liquid form. The latter, being far denser, is more suitable for long-range driving.

⁶ PL 109–58 also provided for a tax credit of fifty cents per gasoline-gallon-equivalent of CNG or liquid gallon of LNG for the sale of CNG and LNG for use as a motor vehicle fuel. The credit began on October 1, 2006 and has recently expired. Note that this rebate (which is over twice the excise tax rate paid now), was to the seller, not the buyer. It is not clear if this could be paid to the ultimate seller – in which case an owner of a trucking company could have qualified for the rebate – or to the wholesaler.

We conducted a literature review that covers energy use, GHG emissions, and conventional pollutant emissions (See Appendix Table A-4 for references). Using this information, we developed a sensitivity analysis that examines how various assumptions can alter the private economic case for substituting new natural gas vehicles for their diesel-fueled counterparts. We limited cost comparisons to heavy-duty trucks only. In the last part of the paper, we examine the case for natural gas trucks from the perspective of social welfare by estimating their social costs relative to diesel trucks and their cost-effectiveness with respect to oil and GHG reductions within the modeling framework of the National Energy Modeling System (NEMS), as modified by RFF to NEMS–RFF. Because the NEMS model only incorporates NGVs by assumption, rather than through economic decisionmaking, we assume a given penetration rate of new vehicles into the fleet over the model’s horizon of 2030. We then track the effects of this penetration on GHG emissions, oil use and, other variables to make offline estimates of the social welfare costs, under various assumptions. As a final analysis, we run the NEMS–RFF model (a version quite close to AEO2009 that includes the stimulus package and a four year advance of new CAFE requirements to 2016) under two sets of data with respect to gas shale resources. One version features resources assumed by EIA and incorporated within NEMS and the other features resource estimates from the Potential Gas Committee (see Brown, Krupnick, and Walls, 2009 for details) that finds far greater resources are available than those in AEO 2009.

This paper is part of a much larger project titled *Toward a New National Energy Policy: Assessing the Options*, hereafter termed the RFF/NEPI project.

Current and Future Use of NGVs in the United States

Of the estimated 110,000 NGVs currently in use in the United States,⁷ the vast majority are heavy-duty trucks (but not long-haul trucks) and other fleet vehicles, including buses, taxis, delivery and refuse trucks, and utility vehicles, which are housed and refueled at a single or a few designated locations. CNG and LNG are largely perceived as being more useful in fleet vehicles and heavy trucks than in other types of vehicles for the following reasons:

⁷ <http://www.anga.us/2010/01/gm-embraces-natural-gas-in-light-duty-pickups/>

- There are only around 840 CNG fueling stations currently operating in the United States, along with 39 LNG stations (28 of which are in California) (Natural Gas Vehicle Association, 2010), compared to over 121,000 gasoline stations, which also may sell diesel fuel and include around 4,000 truck stops selling diesel fuel.⁸ Trucks often travel predictable routes, meaning that the infrastructure for a CNG truck fleet could be concentrated in certain specified areas, whereas the widespread use of CNG in passenger cars would require a much more extensive and costly refueling infrastructure.
- The requisite natural gas tank weight and size is too large for light-duty vehicles (such as passenger cars) to be given equivalent range to gasoline vehicles (but with range superior to electric vehicles) and may involve compromises in cabin size.
- The other major alternative fuel currently in play—electricity—is not appropriate for trucks because of limits to foreseeable battery technology.
- For light-duty vehicles (LDVs), other alternative technologies (such as hybrid electrics and electrics) are already penetrating the fleet or are receiving more attention from the business and government community. Honda currently makes the only factory-built natural gas fueled passenger vehicle sold in the United States.

Accordingly, two categories reflect the bulk of the U.S. transportation fleet that could likely be targeted for CNG and LNG use in the short or medium term: fleet vehicles to be fueled by CNG, which would otherwise be fueled by diesel, and heavy-duty long-haul trucks to be fueled by LNG, which would otherwise be fueled by diesel. Within these categories, the highest mileage vehicles are best able to take advantage of the price advantage of natural gas over diesel.⁹ Fleet vehicles, where range is less important, can be CNG fueled and include transit and school buses, trailer trucks, refuse haulers, and delivery trucks greater than 8,500 lbs. Heavy-duty vehicles appropriate for LNG include class 7 single unit and class 8 combination trucks, such as the 18-wheeler.

⁸ Gasoline stations in 2002 from Bureau of the Census, Industry Statistics Sampler, NAICS 4471: Gasoline Stations. Truck stops from <http://www.dieselboss.com/truckstops.asp>.

⁹ Taxis, because of their high mileage, could also operate more economically on natural gas than most light-duty vehicles could. Conversely, school buses may not be good candidates for natural gas because of their relatively low mileage.

Numerous cities have begun to convert their transit bus and refuse hauler fleets to natural gas, with California cities leading the way. Due in part to air quality management district regulations, 65 percent of all South Coast Air Basin transit buses are now fueled by natural gas. California is also home to 1,268 of the over 2,000 natural gas-fueled refuse haulers in operation nationwide.¹⁰ The San Pedro Bay Clean Air Action Plan that was approved in late 2006 includes a program to replace all diesel trucks based in the ports of Los Angeles and Long Beach with clean alternatives, such as LNG-fueled vehicles, within five years. LNG-fueled 18-wheelers have a presence here as well.¹¹

Various public school districts have also converted their fleets to run on natural gas. After taking part in a pilot alternative fuel vehicles project in the late 1980s, Tulsa Public School District in Tulsa, Oklahoma, now has a fleet of 190 CNG vehicles. In 2005, the Tucson Unified School District in Arizona purchased 70 new CNG buses. The Union of Concerned Scientists reports that 130 school districts in 17 states currently use alternative fuel buses, a large number of which run on natural gas.¹²

Utah has been promoting the use of natural gas vehicles, including private automobiles, by working with a local gas utility to build the fueling infrastructure. Trailing California, Utah currently is one of the top states in number of CNG refueling stations. According to the office of Utah Senator Orrin Hatch, the state is a leader in the promotion of NGVs, and the “governor has helped promote the goal of making Interstate 15 a natural-gas corridor.”¹³ With an influx of nearly \$15 million in federal stimulus funds in 2009, Utah now has 63 stations.¹⁴
http://www.afdc.energy.gov/afdc/fuels/stations_counts.html

Fuel Use and GHG Emissions Differences

One key argument for natural gas vehicles is that they would displace oil use, resulting in energy security benefits. Another is their lower lifecycle greenhouse gas emissions relative to diesel and gasoline vehicles. A third is their lower conventional pollutant emissions. However,

¹⁰ <http://www.cleanenergyfuels.com/refuse/index.html>. (undated, but appears to be a few years old).

¹¹ San Pedro Bay Clean Air Action Plan <http://www.portoflosangeles.org/environment/caap.asp>

¹² http://www.ucsusa.org/clean_vehicles/solutions/cleaner_diesel/success-stories-clean-school.html

¹³ http://hatch.senate.gov/public/index.cfm?FuseAction=PressReleases.Detail&PressRelease_id=5beb6a6b-1b78-be3e-e0b7-f51ae751d683&Month=7&Year=2009

¹⁴ http://www.sltrib.com/news/ci_13218090

standards implemented in 2010 for criteria air pollutants from heavy-duty truck engines will eliminate the advantage of natural gas vehicles in this respect. Thus, in this section we briefly review the quantitative evidence for fuel use and GHG emissions differences. Appendix tables A- to A-3 provide estimates of conventional pollutant emissions before the new standards went into effect.

Current Fuel Consumption and Size of Market of Vehicles that Could Use Natural Gas

Light-duty fleet vehicles represent a relatively small market, with fleet cars accounting for only 4.3 million or 3.2 percent of the 135.9 million cars registered in the United States (table 1). This may understate the importance of the light-duty fleet market, however, as business-owned fleet cars travel more miles on average than privately owned cars (28,000 annually compared to 12,000 for private cars), and tend to be replaced more frequently. A subset of the fleet vehicles—taxis—travels from 80,000 to 100,000 miles per year.

Table 1. Annual Oil Consumption of Vehicles Targeted for Natural Gas Use

Business: fleet car	26,196	4,230,791	22.4	4,947,758,975
Business: fleet truck <19,500 lbs. gross vehicle weight (GVW)	27,372	4,182,765	18	6,360,591,310
Federal government: sedan/station wagon	12,372	111,209	22.4	61,423,114
Federal government: SUV	10,064	120,004	18	67,095,570
Federal government: ambulance	4,967	1,982	18	546,922
Federal government: light truck	5,874	283,835	18	92,624,822
Federal government: medium truck (8,500–26,000 lbs. GVW)	6,418	84,414	14	38,697,789
Total Gasoline	11,568,738,501			
Barrels of Oil	275,446,155			

Source: TEDB 2008.

According to the U.S. Department of Energy's (DOE) *Transportation Energy Data Book* (2008) light-duty fleet vehicles consumed roughly 11.6 billion gallons of gasoline last year (based on average annual mileage, numbers of fleet vehicles, and average fuel economy statistics in the TEDB). This is equivalent to the gasoline produced from 276 million barrels at 42 gallons per barrel. For contrast, total U.S. gasoline consumption is 3.290 billion barrels/year.

Buses and garbage trucks also represent a limited market, with only a little more than 68,000 transit buses¹⁵, 480,000 school buses¹⁶, and over 136,000 refuse trucks operating in the country¹⁷. However, because of the current emphasis on reducing smog-forming emissions, these vehicles have been targeted for natural gas use more because of their presence in urban environments than for their importance in the overall U.S. vehicle fleet. Still, transit buses and garbage trucks can use 10,000 to 15,000 gallons of fuel per year (garbage trucks tend to be at the low end of this range), so switching these fleets to natural gas might be economically favorable.

From Table 2, the 6.8 million single unit trucks registered in the United States in 2007 are mostly used by business and governments in urban areas. Single unit trucks, such as FedEx or UPS vehicles with a combined cabin and cargo body, are driven an average of 12,000 miles per year with fuel economy of 8.2 mpg. These trucks used an estimated 10 billion gallons of diesel fuel.

Combination trucks—those designed for use with one or more trailers—are driven in both urban and rural areas. They account for the majority of heavy-duty vehicle miles travelled, and form an even larger share of heavy-duty vehicle diesel consumption. The 2.2 million combination trucks in the United States accounted for a total 143 billion miles driven in 2006 (Table 3). At an average fuel economy of 5.1 mpg, combination trucks use an estimated 28 billion gallons of diesel annually, which is equivalent to 640 million barrels of oil. For contrast, total U.S. diesel consumption was 1.2 billion barrels per year in 2008.

Heavy single-unit trucks include all single-unit trucks that have more than two axles or more than four tires. Most of these trucks are used for business or for individuals with heavy hauling or towing needs.

¹⁵ Federal Transit Administration 2008. National Transit Summaries and Trends.
<http://www.ntdprogram.gov/ntdprogram/pubs/NTST/2008/pdf/2008%20National%20Transit%20Summaries%20and%20Trends-Complete.pdf>

¹⁶ <http://www.americanschoolbuscouncil.org/index.php?page=fuel-calculator>

¹⁷ http://www.informinc.org/ggt_project1.php

Table 2. Summary Statistics for Heavy Single-Unit Trucks, 1970–2007

Year	Registrations (thousands)	Vehicle travel (million miles)	Fuel use (million gallons)	Fuel economy (miles per gallon)	VMT per registration (miles per year)
1990	4,487	51,901	8,357	6.2	11567
1991	4,481	52,898	8,172	6.5	11805
1992	4,370	53,874	8,237	6.5	12328
1993	4,408	56,772	8,488	6.7	12879
1994	4,906	61,284	9,032	6.8	12492
1995	5,024	62,705	9,216	6.8	12481
1996	5,266	64,072	9,409	6.8	12167
1997	5,293	66,893	9,576	7.0	12638
1998	5,414	67,894	9,741	7.0	12540
1999	5,763	70,304	9,372	7.5	12199
2000	5,926	70,500	9,563	7.4	11897
2001	5,704	72,448	9,667	7.5	12701
2002	5,651	75,866	10,321	7.4	13425
2003	5,849	77,757	8,881	8.8	13294
2004	6,161	78,441	8,959	8.8	12732
2005	6,395	78,496	9,501	8.3	12275
2006	6,649	80,344	9,852	8.2	12084
2007	6,807	81,954	10,035	8.2	12040
<i>Average annual percentage change</i>					
1970– 2007	1.7%	3.0%	2.5%	0.5%	
1997– 2007	2.5%	2.1%	0.5%	1.6%	

Source: U. S. Department of Transportation, Federal Highway Administration, *Highway Statistics 2007*, Washington, DC, 2008, Table VM1 and annual. (Additional resources: www.fhwa.dot.gov)

Note: *Highway Statistics 1999* data were not used.

Table 3. Summary Statistics for Combination Trucks, 1970–2007

Year	Registrations (thousands)	Vehicle travel ^a (million miles)	Fuel use (million gallons)	Fuel economy (miles per gallon)	VMT per registration (Miles per year)
1990	1,709	94,341	16,133	5.8	55202
1991	1,691	96,645	16,809	5.7	57153
1992	1,675	99,510	17,216	5.8	59409
1993	1,680	103,116	17,748	5.8	61379
1994	1,681	108,932	18,653	5.8	64802
1995	1,696	115,451	19,777	5.8	68073
1996	1,747	118,899	20,192	5.9	68059
1997	1,790	124,584	20,302	6.1	69600
1998	1,831	128,159	21,100	6.1	69994
1999	2,029	132,384	24,537	5.4	65246
2000	2,097	135,020	25,666	5.3	64387
2001	2,154	136,584	25,512	5.4	63409
2002	2,277	138,737	26,480	5.2	60930
2003	1,908	140,160	23,815	5.9	73459
2004	2,010	142,370	24,191	5.9	70831
2005	2,087	144,028	27,689	5.2	69012
2006	2,170	142,169	28,107	5.1	65516
2007	2,221	145,008	28,515	5.1	65290

Average annual percentage change

1970– 2007	2.5%	3.9%	3.7%	0.2%
1997– 2007	2.2%	1.5%	3.5%	-1.8%

Source: U. S. Department of Transportation, Federal Highway Administration, *Highway Statistics 2007*, Washington, DC, 2008, Table VM1 and annual. (Additional resources: www.fhwa.dot.gov)

Note: Highway Statistics 1999 data were not used.

^a The Federal Highway Administration changed the combination truck travel methodology in 1993.

GHG Emissions

To determine GHG emissions from the use of natural gas fuels, we take a lifecycle approach, or what is termed “well-to-wheels” (WTW).¹⁸ WTW is usually divided into “well to tank” (WTT) and “tank to wheels” (TTW). WTT includes emissions associated with fuel production, processing, transportation, and distribution. TTW primarily includes vehicle emissions.¹⁹ For fuels relying on natural gas, the majority of WTW emissions come from actual fuel combustion.²⁰

Turning first to tailpipe emissions, CO₂ emissions from gasoline consumption in fleet LDVs and from diesel consumption in heavy-duty vehicles (HDVs) can be estimated based on the carbon content of the fuels. According to the U.S. Environmental Protection Agency (EPA), gasoline has a carbon content of 2,421 grams per gallon, while diesel has a carbon content of 2,778 grams per gallon.²¹ This amounts to approximately 8.8 kg CO₂ per gallon of gasoline burned, and 10.1 kg CO₂ per gallon of diesel. Given the above estimates, fleet LDVs generate approximately 102 million metric tons of carbon dioxide (mmtCO₂) each year, while HDVs generate 389 mmtCO₂. For comparison, the United States generated 6,021 mmtCO₂ in 2007, and 7,282 million metric tons CO₂ equivalent of all GHGs.

To estimate the lifecycle GHG emissions of CNG and LNG vehicles, several factors need to be taken into account. First, the type of natural gas used as a feedstock can have a significant impact on WTT emissions. According to a California Energy Commission (2007) report, the production and delivery of CNG produced from North American natural gas generates 48 percent lower GHG emissions than CNG produced from regasified imported LNG. CNG

¹⁸ Although carbon dioxide is the most discussed greenhouse gas, all such gases affect global warming, albeit to various degrees. Methane is of particular concern when assessing natural gas vehicles, as methane is the main component of natural gas and has several times the global warming potential of carbon dioxide. Most analyses of GHG emissions use factors to convert emissions of each of these gases into CO₂-equivalent units. We do the same thing here.

¹⁹ Not all studies make this distinction, but where they do, it is useful because this disaggregation permits the source of differences in estimates to be identified.

²⁰ However, omitting pre-combustion emissions from the analysis would tend to overstate the GHG benefits of these fuels relative to gasoline and diesel. Because CNG and LNG vehicles also require different engine parts and fuel storage tanks than their gasoline and diesel counterparts, the manufacturing of the actual vehicles may also generate different levels of emissions. However, most studies assume that CNG and LNG vehicles are sufficiently similar to gasoline and diesel vehicles that the differences associated with vehicle manufacture are negligible, particularly in comparison to WTT and TTW emissions.

²¹ <http://www.epa.gov/oms/climate/420f05001.htm>

produced from imported LNG produces greater GHG emissions because of transport to the United States in tankers and energy-intensive liquefaction and regasification of LNG. When LNG is used directly as a heavy-duty truck fuel, it is more competitive with CNG because the liquefaction and regasification processes are avoided. Yet there are still significant emissions because without an LNG pipeline infrastructure, it must be transported to refueling stations by tank trucks. The recent augmentation of shale gas resources leads to predictions (Brown and Krupnick 2010) that the United States will become a net exporter of natural gas by 2030. Thus, the LNG import pathway that so reduces the CO₂ advantage of natural gas may be of little importance.

Another key distinction in lifecycle emissions is the feedstock source. Extracting natural gas from gas shale, for example, requires horizontal drilling which is more energy intensive than standard vertical drilling. This issue is particularly relevant given the recent and projected future increases in domestic gas shale production. Using biomethane or flared/vented gas can dramatically lower the emissions associated with natural gas fuels, because the capture of biomethane prevents a potent greenhouse gas from being released into the atmosphere from landfills or other waste facilities. Indeed, CNG and LNG produced from biomethane can actually be carbon negative.

Estimates of the emissions reductions from CNG and LNG during the TTW phase also vary significantly, mainly because different drive cycles can be used to measure CNG or LNG emissions. The drive cycle used in a study can have a particularly significant impact for heavy-duty vehicle tests. Davies et al. (2005) find that CNG generates higher levels of tailpipe GHG emissions than diesel for certain HDV applications under a cycle similar to the central business district driving cycle. Different drive cycles can imply different GHG emissions benefits because CNG and diesel vehicles have different relative fuel economies under different driving conditions. Different engines also have different CO₂ emissions.

Emissions Relative to Base Fuel

Table 4 provides the results of our literature review on lifecycle GHG emissions differentials by CNG and LNG versus various types of gasoline and diesel fuels, by LDV and HDV vehicle types.

Light-Duty Fleets: CNG Relative to Gasoline

As shown in Table 4, the comparison of emissions from CNG versus gasoline LDVs has had the most attention devoted to it. Overall, the studies we reviewed credit CNG with up to a 30

percent reduction in GHG emissions (not including the estimate for flared gas-derived CNG) relative to gasoline. There is a significant amount of variation in the percentage reduction estimates however, because of the factors mentioned above that complicate the estimates of emissions from CNG vehicles, and due to differences in the baseline gasoline vehicles used for comparison. One study (GM 2005) assesses a scenario that is particularly unfavorable to natural gas, where the gas is imported from outside North America as LNG and is compared to gasoline in a direct injection vehicle. CNG emissions are found to be slightly larger than those from the gasoline vehicle. Again, such an unfavorable view of CNG CO₂ emissions is dependent on LNG imports, which can be expected to be unimportant in the future.

Studies that delineate the division of emissions reductions between WTT and TTW grant CNG an unambiguous and large advantage over gasoline in the TTW portion of the lifecycle assessment.

This part of Table A-4 also shows that the type of gasoline engine matters. Again, the GM study shows that a direct injection engine performs better than a DOD engine with respect to GHG emissions, which can reduce the overall GHG benefit of CNG to 10 percent over gasoline.

TABLE 4: GHG Emissions Reductions Relative to Baseline Fuel

SOURCE/REFERENCE	Baseline Fuel	Well to Tank	Tank to Wheels	Well to Wheels
LDV CNG				
Delucchi 2003	Gasoline	--	--	28%
ANL 1999	Gasoline	-11 - 18%	11 - 27%	7 - 25%
Beer 2004	Premium Unleaded Petroleum	--	15%	--
CEC 2007, NA NG	Reformulated Gasoline	46%	26%	30%
CEC 2007, Remote NG	Reformulated Gasoline	-5%	26%	20%
EUCAR 2004	Gasoline	--	22%	--
GM 2005, NA NG	DOD Reformulated Gasoline	22%	--	21%
GM 2005, NA NG	DI Reformulated Gasoline	22%	--	10%
GM 2005, NNA NG	DOD Reformulated Gasoline	-23%	--	10%
GM 2005, NNA NG	DI Reformulated Gasoline	-23%	--	-1%
GREET 1.8b, NA NG	Conventional and Reformulated Gasoline	6%	17%	15%
GREET 1.8b, NNA NG	Conventional and Reformulated Gasoline	-44%	17%	5%
GREET 1.8b, NNA FG	Conventional and Reformulated Gasoline	635%	17%	144%
Weiss 2000	Gasoline	14%	--	--
HDV CNG				
Delucchi 2003	Diesel	--	--	23%
Beer 2000	Diesel	--	2 - 6%	--
CEC 2007, NA NG	Ultra Low Sulfur Diesel Urban Buses	32%	21%	23%
CEC 2007, Remote NG	Ultra Low Sulfur Diesel Urban Buses	-31%	21%	11%
ROSENFELD AND JACKSON 2008, NA NG	Ultra Low Sulfur Diesel Heavy Duty Trucks	53%	22%	29%
ROSENFELD AND JACKSON 2008, NNA NG	Ultra Low Sulfur Diesel Heavy Duty Trucks	-11%	22%	15%
ROSENFELD AND JACKSON 2008, BG	Ultra Low Sulfur Diesel Heavy Duty Trucks	366%	22%	95%

Resources for the Future

Krupnick

HDV LNG				
Beer 2000	Diesel	--	-17 - 3%	--
CEC 2007, NA NG	Ultra Low Sulfur Diesel Urban Buses	-3%	20%	16%
CEC 2007, Remote NG	Ultra Low Sulfur Diesel Urban Buses	-26%	20%	11%
ROSENFELD AND JACKSON 2008, NA NG	Ultra Low Sulfur Diesel Heavy Duty Trucks	22 - 57%	20%	21 - 28%
ROSENFELD AND JACKSON 2008, NNA NG	Ultra Low Sulfur Diesel Heavy Duty Trucks	-40 - 15%	20%	7 - 14%
ROSENFELD AND JACKSON 2008, BG	Ultra Low Sulfur Diesel Heavy Duty Trucks	370%	20%	95%

NA: North American
 NNA: Non-North American
 FG: Flared Gas
 BG: Biog

Heavy-Duty Fleets: CNG Relative to Diesel

The story for diesel is less complex only because there are so few relevant studies. For the full lifecycle, two studies find a 23 percent benefit when CNG is used to fuel the heavy-duty vehicle, with smaller benefits when the feedstock is foreign LNG (where, again, this source of LNG may be much less important than previously forecast). In 2005, TIAX, a company that commercializes technology, compared the costs of operating heavy-duty vehicles using diesel power and natural gas. The study, prepared for the California Natural Gas Partnership²², finds a 29 percent reduction in GHG emissions from natural gas compared to a diesel counterpart. It is important to note, however, that the TIAX study is specific to California, as is a 2007 study we looked at, also prepared by TIAX, and published by the California Energy Commission (CEC). Based on the estimates of the emissions benefits of CNG in light-duty vehicles, the TIAX estimates may be overly optimistic about potential GHG benefits of CNG. In particular, the WTT GHG emissions benefits of CNG should be roughly similar for HDVs and LDVs, because from the standpoint of emissions, the production and distribution of diesel and gasoline are similar.²³ The TIAX WTT emissions estimates are notably higher than any other studies, perhaps because of California's relatively clean electricity generation mix.

Comparing results for LDVs and HDVs using CNG for the studies that examine both (CEC 2007 and Delucchi 2003), GHG emissions differentials are larger for LDVs examined by both studies, because diesel, with its higher energy density and more efficient combustion engine, is more fuel efficient than gasoline, although its CO₂ emissions are greater on a per gallon equivalent basis.

Cost Differences: Heavy-Duty Trucks

The discussion here establishes the parameters we will use in the sections below to estimate private and social returns to substituting natural gas-fueled heavy trucks for their diesel counterparts. Just as the full fuel cycle must be taken into account when estimating the emissions reductions of natural gas-fueled vehicles, all lifecycle costs should be considered in determining

²² (http://www.tiaxllc.com/reports/HDDV_NGVCostComparisonFinalr3.pdf).

²³ According to GREET 1.8b (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model), "well-to-pump" GHG emissions are 20,022 grams/mmBtu for gasoline and 18,249 grams/mmBtu for diesel.

their economic viability. Lifecycle costs include the vehicle purchase price, maintenance costs, and fuel costs. The lifespan of the vehicles, as well as vehicle miles traveled (VMT) are also important factors, as they determine how large the fuel savings can be. Similarly, the discount rate used in assessing the cost-effectiveness of NGVs determines the importance of future fuel cost differentials, relative to vehicle investment costs.

In performing our analyses, we did not include the costs of building or converting refueling infrastructure. We assumed these costs would be included in the price of natural gas at the fuel pump. Thus, one can implicitly address such costs by manipulating fuel price differentials between diesel and natural gas.

Fuel Costs

The component of lifecycle costs that has received the most attention recently is the fuel cost. LNG and CNG vehicle advocates claim that owners of NGVs will enjoy lower and more stable fuel prices than owners of gasoline and diesel vehicles. For instance, the Natural Gas Vehicle Association claims on their website that the fuel costs of using natural gas instead of diesel can be “one-third lower.” In fact, in California, where truckers can fill up at several stations with LNG, per diesel equivalent LNG is \$0.75/gallon equivalent cheaper for the independent trucker and \$1/gallon cheaper for the fleet vehicle.²⁴ Indeed, when oil prices were at their highest in 2008 and diesel was \$4.75/gallon, LNG was \$2/gallon cheaper than diesel even though natural gas was priced relatively high at \$11–\$13 per 1,000 cubic feet (mcf) of gas.¹⁷ Organizations that are critical of these alternative fuels cite fuel cost differences (including efficiency differences, rebates/subsidies, and price) of around fifty cents per gallon, with estimates of a cost differential as high as \$1.73 per gallon from organizations favorable to these fuels. However, the modal estimates are in the \$0.50 to \$1.00 per gallon range. Daimler–Chrysler, for their new series of Class 8 LNG trucks, cites a savings of only \$6,000 per year, but the press release refers to trucks working in the Port of Los Angeles so their mileage may be very limited.²⁵ As a benchmark, a long-haul heavy-duty truck traveling 70,000 miles a year and with mileage of five miles per gallon would be using 14,000 gallons and thus saving \$14,000 at a \$1/gallon equivalent fuel price differential.

²⁴ Interview with Mitchell Pratt, Clean Energy Inc., November 17, 2009.

²⁵ <http://green.autoblog.com/2009/07/21/daimler-introduces-new-freightliner-natural-gas-truck/>

Irrespective of these price differentials, there are tax benefits for CNG and LNG. As noted above, at least until the end of 2009, LNG sellers were eligible for a credit of fifty cents per gallon from the federal government (and there are state programs providing per-gallon credits against excise taxes).²⁶ It is likely that some of these benefits would be passed on in lower fuel prices.

There are reasons to think that the recent fuel price gap could widen in the future. Greater accessibility and technological advances in recovering shale gas could keep prices of LNG stable or even drive them lower, while prices for oil and, therefore, diesel fuel are believed to be on an upward trend. A recent presentation by IHS Global Insight (2010) shows that over the long term the ratio of oil to gas prices may rise to about three to one between now and 2030.²⁷ However, natural gas prices have a history of instability and CNG has, at times, been more expensive per gallon equivalent than its diesel counterpart.

New Vehicle Costs

Several papers address the price differentials without subsidies for a Class 8 truck fueled by either diesel or natural gas. According to estimates on line and in conversations with experts, the differential ranges from \$70,000 to \$100,000 (for early models) more than the price of a diesel truck of about \$100,000.²⁸ Detailed information on vehicle prices puts the cost differential at \$70,000 for a Westport compression-type LNG engine, with a newer technology relying on an 85 percent LNG /15 percent diesel fuel mix, selling for only \$35,000–\$40,000 above its diesel counterpart²⁹. The price differential for a smaller version of the Class 8 truck (termed a “Baby 8”) or a Class 7 truck (both using spark plug technology) is in the \$40,000 range.

Such cost differential estimates may well be on the high side for several reasons. For one, NGVs have not yet benefited from economies of scale as gasoline and diesel vehicles have, so

²⁶ Thirty-five state governments, as well as many regional and local governments, offer vehicle buyers and owners incentives to buy and operate natural gas vehicles. These incentives include tax deductions/credits, reduced license fees, reduced vehicle sale taxes, and lower registration fees.

²⁷ Presentation by Mary Novak, IHS Global Insight, at the EIA 2010 Energy Conference, April 6–7, 2010, Washington, DC.

²⁸ Total Transportation Services recently purchased 22 additional Kenworth T800 LNG trucks to expand its fleet of 8 such trucks purchased six months before. This purchase suggests that fuel and maintenance costs were manageable (*LandLine*, March/April, 2009).

²⁹ Interview with Michael Gallagher, Cummins Westport, November 2009.

costs might decrease significantly if demand for NGVs increases. Second, stricter standards on diesel emissions, which take effect in 2010, may raise prices on diesel vehicles. Furthermore, future costs are highly uncertain. Natural gas engine technologies are less mature than diesel and gasoline technologies, and it is uncertain which particular NG engine types will be most successful in the future. For example, as of 2010, spark-ignited, lean-burn CNG and LNG engines, which have been the most common designs, are no longer being produced because they cannot meet 2010 emission requirements. They have been replaced by stoichiometric spark-ignited engines with cooled exhaust gas recirculation (EGR). About 5,000 of these vehicles were in service as of the end of 2009. Operating in the other direction are attempts to stimulate clean diesel technologies. For instance, trucking companies can get \$20,000 rebates for purchasing new clean diesel trucks operating in the Port of Los Angeles.

Maintenance Costs

It is difficult to compare maintenance costs of new Class 7 and 8 trucks operating on diesel and natural gas because U.S. experience with these types of trucks is limited. Early experience with single-unit trucks (Class 7) by UPS was extensive, but occurred in 2002. UPS found that maintenance costs at one facility were 29 percent higher for their CNG vehicles compared to their diesel trucks, but with greater attention to the vehicles at another facility, maintenance costs were only 6 percent greater (Chandler, et al. 2002). Evidence is mixed for transit buses and fleet vehicles as well as for long-haul trucks. Some transit bus studies show higher and others lower maintenance costs. Again, for buses, studies of comparative operating costs (fuel and maintenance costs) show costs to either be higher for NG buses or the same as for diesel buses (Hesterberg, Bunn, and Lapin 2009). By default, we assume they are equivalent.

Fuel Economy

The energy content of LNG is 23 percent lower than diesel for tractor trailers, and in this range for delivery trucks and buses (Hesterberg, Bunn, and Lapin 2009). CNG and LNG fuel tanks are heavier than their diesel counterparts (adding about 500 pounds per tank, increasing truck weight and further reducing fuel economy) and the spark engines have lower efficiency than their compression-based counterparts, which in turn are more similar to a diesel engine.

According to the U.S. Department of Transportation (DOT), fuel economy of diesel Class 8 vehicles was 5.1 mpg (Table 3) in 2007. LNG equivalent fuel economy appears to be in the same range.³⁰

Miles per Year and Vehicle Lifetime

There are different estimates of how far the average class 8 vehicle is driven per year. One estimate is about 70,000 miles based on DOT data (Table 3). Another estimate, which uses Census data from 2002, features average VMTs of about 90,000 miles per year. Also from this source, which provides distribution data, the vehicle at the mode of the distribution is driven about 125,000 miles per year and about one-third of the fleet drives this distance or more. We assume VMT would not differ based on fuel use; however, the shorter range for trucks using CNG and LNG might result in fewer VMTs. For calculating fuel savings on a lifetime basis, we estimate vehicle lifetime to be 15 years,³¹ based on information from the DOT. There is anecdotal information that truck owners expect their CNG and LNG vehicles to last longer.³²

Net PDV Costs and Payback Periods

We use two complementary methods to examine the economics of purchasing an LNG vehicle compared to a diesel vehicle from the point of view of the buyer (not necessarily from society's point of view): the present discounted value (PDV) approach and the payback period approach. The former method compares the purchase price differentials of diesel vs. LNG vehicles (first costs) with the stream of annual cost savings over the vehicle's lifetime. These annual cost savings must be discounted, using a chosen interest rate, to reflect the costs of waiting for those savings to accrue.

The second method is our main method and involves calculating payback periods. Given a particular rate of interest and other variables described above, one can calculate the number of years of fuel savings (or the payback period) that will exactly offset the higher up-front costs of

³⁰ Interview with Mitchell Pratt, Clean Energy Inc., November 17, 2009.

³¹ From Tables 3 and 5, 151,000 new combination trucks (Class 8) were purchased in 2007, with registrations in 2007 of 2.221 million combination trucks. Thus, new vehicles are 6.8 percent of the fleet. Assuming this is an equilibrium situation, where truck retirements and purchases are equal, truck life averages 14.7 years. Industry analysts offer 18–20 years as a realistic average for truck life.

³² *Landline*, March/April, 2009

an LNG vehicle. This type of calculation is useful because, based on behavioral studies, we observe that people demand rapid payback periods, therefore departing from the PDV calculations that a fully rational decision-maker would make.

In both cases, we need to choose a discount rate.³³ Following decisions made in the larger RFF/NEPI study of which this paper is a part, we examine three rates:

- 31 percent. This is the implicit rate of interest used by the National Energy Modeling System (NEMS). This rate derives from actual market data showing that buyers demand a payback of investment costs through fuel savings within three to four years and that fuel savings during those first few years are discounted at 10 percent. Implicitly, these factors lead to a rate of discount of 31 percent. Why buyers are so risk averse is an object of some controversy. Some assert that there are (or are expectations of) hidden costs of such technologies— doubtlessly true since experience with them is so limited. Others assert that there are market failures, such as constraints on borrowing. In the latter case, one would rightly use a lower discount rate to reflect this situation from society's point of view.
- 10 percent. In the RFF/NEPI study, we use a rate of 10 percent is used to reflect partial market failure.
- 5 percent. Social discount rates used to evaluate public projects are often in the range of 3% 5%. Although the substitution of natural gas for diesel vehicles is not a public project, it can confer major public benefits in terms of emissions reductions and energy security. Of course, buyers do not use such a rate. Thus, we make calculations with this rate to illustrate the efficiency of LNG truck subsidies or mandates from society's perspective, assuming complete market failures.

³³ We discuss how to choose this rate in the RFF/NEPI report. This report uses three cases to address the energy paradox, which refers to apparently profitable energy efficiency investments which are often rejected by businesses and consumers. The no market failure case (modeled using a 31 percent discount rate) is based on observed behavior of consumers as embodied in NEMS. In contrast, the complete market failure case can be represented by using the social discount rate (5 percent). Here the energy paradox is explained entirely by market failures (e.g., consumers with short horizons or imperfect information about energy saving benefits). In the absence of any policy, there would be inadequate investment in energy efficiency because consumers as individuals value it less than society does. The partial market failure case is represented by a 10 percent discount rate.

We find that under the most favorable conditions, an LNG truck could be economic. Using a 5 percent interest rate and fuel savings of one dollar per gallon for LNG, lifetime fuel savings are \$132,000. This compares to a price differential against a new LNG vehicle that might be up to \$100,000. Using a 10 percent rate and a cost savings of only fifty cents per gallon, the PDV costs are negative.

Table 5 shows payback periods for various assumptions that are within the limits of existing analysis and literature review. There are five parameters of primary interest. Natural gas vehicles are assumed to sell for \$35,000 to \$100,000 (not including subsidies or rebates) more than diesel vehicles, with \$70,000 as a best guess. A best guess for natural gas and diesel fuel economy is 5.1 diesel equivalent gallons (DEG), with a range from 4.6 DEG to 5.6 DEG. Interest rates are given at the “social rate” of 5 percent as well as rates assuming partial and no market failure of 10 percent and 31 percent. Our best guess is that there is some market failure, so that implies a 10 percent discount rate applied to fuel savings. The fuel price differential is the difference between diesel and NG price at the pump in DEG terms (without accounting for any subsidies or changes in taxes). Figures in the literature range from \$0.50 to \$2.00; we chose a current average price differential (\$0.75) as a best guess. Finally, while we generally assume average VMTs are 70,000 miles per year, for the best estimates of investment cost differentials (\$70,000), we vary VMTs from 70,000 to 125,000 per year. As a large segment of the market apparently is in this high mileage group, and the more a truck is driven the greater the cost savings is from using natural gas, it may be that for the high mileage segment, payback periods are acceptable, whereas for the lower mileage segment of the market, they are not.

The table arranges these parameters from the most optimistic on the left to the least optimistic on the right, and shows a minimum payback period of 1.6 years and a maximum of an infinite payback period. The combination of best-guess assumptions (either using the 70,000 VMT estimate or the 100,000 mile estimates yields payback periods of 12 and five years, respectively.

Given that the lifetime of LNG trucks may be around 15–20 years, payback periods longer than 15–20 years cannot be economic under any assumptions about the discount rate. It is

useful, therefore, to examine the cells for which the pay back is under four years, paying particular attention to the columns with a 10 percent or a 31 percent interest rate.³⁴

Cells in yellow indicate a payback period under four years, while those in red have payback periods longer than 15 years. Not surprisingly, most of the yellow cells are concentrated in the first three columns, where we assume that the vehicle price differential is only \$35,000 and that fuel prices differ by \$1.50 per gallon equivalent. Focusing on the benchmark vehicle price differential columns (\$70,000) and assuming equal fuel economy of LNG and diesel trucks, fuel price differentials need to be at the upper end of the range shown to meet the four-year payback criterion. Higher price differentials are also needed when interest rates are higher. Note that at the high price differential but using the 31 percent discount rate, the very high mileage segment of the market enjoys a payback period under four years.

A lower interest rate increases the social value of fuel savings, implying a lower cost for any policy that promotes energy efficiency investments. Indeed, costs could even become negative. Inspection of the table reveals that the payback periods are least sensitive to the VMT change, then progressively more sensitive to the interest rate, fuel prices, vehicle prices, and most sensitive to the NG fuel economy.

In the above analysis, we assume zero fuel price subsidies beyond any current tax differentials, and no rebates or other forms of subsidies on new vehicles. What difference would such subsidies make?

As noted briefly above, PL 109-58 provides for an income tax credit of up to 50 percent of the incremental cost of a new, dedicated alternative fuel vehicle, plus an additional 30 percent if the vehicle meets certain tighter emission standards. These credits would range from \$2,500 to \$32,000, depending on the size of the vehicle. The credit is effective on purchases made after December 31, 2005 and expires on December 31, 2010.

³⁴ One of our reviewers notes that owners of these very high mileage trucks may demand payback periods of a year to switch to LNG. If so, none of our combinations of assumptions would induce such purchases without some form of subsidy.

Table 5. Sensitivity of Payback Periods to Assumptions

		Vehicle Cost Differential = \$35,000			Vehicle Cost Differential = \$70,000			Vehicle Cost Differential = \$100,000		
		Fuel Economy = 5.6 mpg	Fuel Economy = 5.1 mpg	Fuel Economy = 4.6 mpg	Fuel Economy = 5.1 mpg			Fuel Economy = 5.6 mpg	Fuel Economy = 5.1 mpg	Fuel Economy = 4.6 mpg
		VMT=70K			VMT=125K	VMT=90K	VMT=70K	VMT=70K		
Interest Rate = 0.05	Fuel Price Differential = \$1.50	1.62	1.82	2.14	2.05	2.91	3.82	5.03	5.70	6.81
	Fuel Price Differential = \$.75	3.04	3.82	5.54	4.33	6.29	8.52	10.27	13.63	23.17
	Fuel Price Differential = \$.50	4.30	6.03	11.98	6.89	10.36	14.62	15.93	26.73	-
Interest Rate = 0.10	Fuel Price Differential = \$1.50	1.73	1.95	2.31	2.22	3.22	4.36	5.99	6.98	8.75
	Fuel Price Differential = \$.75	3.39	4.36	6.74	5.03	7.90	11.96	16.30	37.30	-
	Fuel Price Differential = \$.50	4.99	7.48	22.72	8.88	16.54	-	-	-	-
Interest Rate = 0.31	Fuel Price Differential = \$1.50	12.09	-	-	3.30	6.35	-	-	-	-
	Fuel Price Differential = \$.75	-	-	-	-	-	-	-	-	-
	Fuel Price Differential = \$.50	-	-	-	-	-	-	-	-	-

Note: Yellow boxes have a payback period of under 4 years. Pink boxes have a payback period beyond 15 years or (with dashes) infinite.

For an optimistic case, assume that the rebate could reduce the price of a new LNG vehicle to only \$20,000 more than the comparable diesel truck. The payback period (assuming equal fuel economy to diesel, an interest rate of 10 percent, 70,000 VMT and a fuel price differential of \$0.67) drops from 8.2 years without the rebate to 2.6 years with it. This clearly indicates that rebates of this size, in the presence of relatively low market price differentials and under the given assumptions, can make a big difference in the purchase decision.

Rebates on vehicle purchase price can also be combined with subsidies for natural gas as a transportation fuel (as already exist in some states and on the federal level). Referring to the federal fuel rebate program discussed above, if the price at the pump falls by the full amount of the rebate (in this case, \$0.50), this significantly shifts the fuel price differential. To illustrate, with a combined \$1.50 fuel price differential and assuming equal NG/diesel fuel economy, a vehicle price differential of \$70,000 and an interest rate of 5 percent, the payback period would fall from 6.0 years to 3.8 years. With a 10 percent interest rate, the payback period would fall from 7.5 to 4.4 years, with other things equal. Coupling this per-gallon subsidy with the new truck rebate further lowers the payback period from 4.4 years to 2.3 years. Clearly, combining these two incentives can make a significant difference to the payback period and, therefore, the penetration of LNG trucks.

NEMS and Natural Gas-Fueled Heavy-Duty Trucks

Currently, the NEMS model does not incorporate consumer decisions to purchase any vehicle powered by either CNG or LNG (see Appendix A for documentation of the Freight Module in NEMS). Instead, the Energy Information Agency makes assumptions about the rate at which such vehicles penetrate the fleet and hardwires such assumptions into the model. Changes in those assumptions can affect the price of natural gas, as well as impact markets that would be affected by that price change.

In this section, we define an aggressive NG truck penetration rate, model that penetration in NEMS, and report on what happens to energy-related CO₂ emissions and oil consumption—as well as other variables of interest—when compared to the RFF/NEPI reference case (which is very similar to the 2009 Annual Energy Outlook with the stimulus package included). We also look at a modification of the reference case with what we consider to be more realistic and recent

estimates of natural gas reserves, based on data from the Potential Gas Committee.³⁵ In addition, we present a methodology for estimating social costs of such penetration. Finally, we provide estimates of cost-effectiveness according to cost per barrel of oil or ton of CO₂ emissions reduced.

Note that we are not assuming any policy is in place to mandate or subsidize the penetration of such vehicles. There are many examples of government policies to advantage particular types of vehicles in these ways, however, so one can imagine that such a policy could be implemented. Note also that we have not modeled any government policies that might indirectly advantage NG vehicles, such as a carbon tax or cap-and-trade policies.

The Reference Case

NEMS forecasts the demand and supply of new diesel trucks, and tracks trucks' age and retirements, operating costs, purchase prices, and more. The model bases decisions to purchase these vehicles vis-à-vis other types by assuming a four-year payback requirement, with a 10 percent discount rate applied to costs or savings occurring during the four years.

In the reference case, the stock of Class 7 and 8 freight trucks is projected to be 5.21 million in 2010. Almost all of these are diesel powered, with about 250,000 gasoline-powered and the rest split between natural gas and propane. Sales in 2010 are projected to be 260,000, 96 percent of which are diesel-fueled and the rest gasoline-fueled. By 2030, the stock is expected to rise to 7.1 million vehicles with sales of 370,000 vehicles—nearly all burning diesel.

According to NEMS, all freight trucks (classes 3–8) traveled 248 billion miles in 2007, with an assumed efficiency of 6.0 mpg and energy use of 5.15 quadrillion Btu (quads Btu), for an oil equivalent of 2.46 mmbd. By 2010, oil use is down to 2.27 mmbd. In 2010, all diesel freight trucks are projected to use 4.5 quads Btu, 18 trillion Btus of which will be used by CNG freight vehicles. Class 7 and 8 trucks make up most of this overall energy use (4.06 quads Btus in 2010).

³⁵ Updating the model to reflect these new relatively low-cost resources lowers the price of natural gas by about \$2/mcf in 2030.

Setting Penetration Rates for Natural Gas-Fueled Trucks

To examine the impact of a substantial penetration of natural gas trucks, we developed a “bounding” scenario that assumes that 10 percent of the new class 7 and 8 vehicles will be powered by natural gas in 2011, 20 percent of new purchases in 2012 will be natural gas powered, and so on, so that by 2020 and for the following 10 years, every new class 7 and 8 truck purchased would be powered by CNG/LNG.³⁶ In this scenario, the stock of Class 7 and 8 freight trucks fueled by NG is projected to rise to 5.15 million vehicles by 2030, with another 1.9 million diesel vehicles still remaining in the stock. Beginning in 2011, sales of NG vehicles are 30,000, rising by 2030 to 400,000 new NG vehicle sales. This scenario results in 32 percent of the heavy-duty truck fleet fueled by natural gas in 2020, rising to 73 percent by 2030.

The baseline fuel economy for the stock of diesel and natural gas heavy-duty trucks is very important to the results of the bounding scenario. In 2011, this fuel economy is 5.6 and 7.2 mpg gasoline–gallon equivalent (GGE) for diesel and natural gas trucks respectively, rising significantly for diesel (to 6.5) by 2030 (only to 7.3 for natural gas trucks). New diesel and natural gas heavy-duty trucks in 2011 are just slightly more efficient, at 5.7 and 7.3 mpg GGE, rising to 6.6 for diesel and staying constant for NGVs by 2030. These assumptions are slightly different from those we developed in the section on Net PDV costs and payback periods.³⁷

VMTs per year are also an important input to welfare costs and oil and CO₂ reductions. In NEMS, the average³⁸ diesel truck drives an average of 37,000 miles in 2011 (this includes lower-mileage Class 7 trucks in addition to the high-mileage class 8 trucks), rising to 42,000 miles in 2030. This seems like an underestimate relative to the information developed in the section on Net PDV costs and payback periods.

³⁶ Starting in 2011 at 10 percent of the new vehicle cohort assumed to be fueled by natural gas, we increased the percentage by 10 percent each year, so that in 2020 100 percent of the new vehicle cohort was assumed to be fueled by natural gas.

³⁷ In the previous section, we set the various parameters based on literature and some expert judgment. Here, we are using parameters embedded into NEMS and these change every year. Thus, the analyses in the two sections are not fully comparable. The earlier discussion provides insights into what it takes to get penetration. Here, we illuminate what happens given penetration.

³⁸ NEMS has no information on the distribution of miles driven.

Calculating Costs

Accurately calculating the economic cost of a transportation policy is complicated, given that the market impacts and effects of existing market distortions must be captured. Because natural gas vehicle choice is not determined economically in NEMS–RFF, it is not practical to make all these calculations. We do make the main calculation, however. We first calculate the PDV of the difference between the first (vehicle) cost and fuel costs (i.e., lifetime costs net of fuel taxes) of a diesel vehicle and an NG vehicle. We multiply PDV times the number of new natural gas-fueled vehicles, summed over each new vehicle year cohort and make a separate adjustment for the benefits that higher trucking prices will have for rail and barge transport.³⁹

As a result of the increased cost of moving goods by truck (following rising natural gas prices in our bounding scenario and any unsubsidized cost differentials in natural gas versus diesel trucking), we would expect some goods to move from freight to rail, barge, or other transportation substitutes, where such substitution lowers the overall welfare cost. NEMS does not capture this substitution. However, we can capture this effect using a modified demand elasticity for trucked goods. In the RFF/NEPI report, we used 0.2 for other purposes, so we use it here as well. This assumption allows us to make the necessary cost adjustments. For clarity, we present both the simple and adjusted welfare measures.

For the sake of consistency with other scenarios in this project that rely on NEMS, we use certain NEMS outputs to calculate cost of diesel and natural gas vehicles. For each forecast year starting in 2011, these variables include:

- the price of diesel fuel (GGE);
- the price of natural gas (converted from mmbtu to gallons using 0.125 mmbtu's per gallon);
- the fuel efficiency of heavy duty diesel and natural gas trucks;
- the average VMT's for these vehicles;
- the stock of diesel and natural gas fueled heavy trucks;

³⁹ Economic theory shows that if one captures the welfare losses or gains in the market directly affected by a policy change, the secondary impacts on other markets, that occur through price effects, such as what we have here, can be ignored in the welfare calculation (absent preexisting market distortions in these secondary markets). Such effects can be important in any equity or other analysis of the effects of the policy, but not in the efficiency-based estimates. In the case here, the directly affected market is the market for trucked goods.

- the (assumed) number of new natural gas trucks substituting for new diesel trucks; and
- the fuel tax rate on diesel⁴⁰

Variables defined outside the model include the discount rate for bringing the fuel cost savings for a new NG vehicle back to the year in which the vehicle was purchased (either 31 percent or 10 percent), the discount rate used to bring the net costs for each new vehicle cohort year back to 2007 (we use 5 percent, consistent with use of this rate in the overall RFF/NEPI project), the price (first cost) of diesel and natural gas fueled heavy duty trucks and truck lifetime.

NEMS–RFF Results, using Reference Case Natural Gas Resource Estimates

Oil and Carbon Implications

Beginning in 2011, the substitution of natural gas trucks for diesel Class 7 and 8 trucks is projected to reduce carbon emissions, primarily because natural gas has lower emissions than the diesel it is replacing, and possibly as a consequence of higher prices for natural gas. Indeed, carbon emissions in the transportation sector fall 7 percent relative to reference case levels in 2030. In addition, higher demand for natural gas increases natural gas prices, which in turn leads to higher electricity prices, reduced electricity use, and lower carbon emissions.

As natural gas becomes more expensive, however, fuel substitution in power generation also occurs. This could lead to *increased* carbon emissions, depending on whether the fuel being substituted for natural gas is more or less carbon-intensive. In NEMS–RFF, the use of natural gas is largely replaced by carbon-free nuclear power, and the net effect is a 3 percent reduction in energy-related CO₂ emissions from the electricity sector. Overall, there is a net reduction in all energy-related CO₂ emissions in the U.S. of 2 percent.

Considering oil use, total petroleum consumption falls 12 percent (18 mmbd in 2030 in the reference case compared to 15.8 mmbd for the NG vehicle scenario). Because there already are significant reductions in petroleum use from 2007 to 2030 in the reference case (about two

⁴⁰ NEMS–RFF represents these rates, which include both state and federal taxes, in geographically disaggregate form. To simplify the analysis we take an average of these rates, which is \$0.44/GGE.

mmbd), the bounding scenario reduces oil use from 2007 by over four mmbd, from 19.9 mmbd to 15.8 mmbd. Imports drop by even larger amounts.

Effects on the Energy-Using Sectors

Inevitably, the bounding scenario leads to a dramatic increase in demand for natural gas in the transportation sector, rising from 0.08 quads Btus in 2030 in the reference case to 4.2 quads Btus in the scenario. As a result, the price of natural gas is 16 percent higher in 2030 than it was in the reference case. Not surprisingly, the price of diesel falls (13 percent compared to the reference case in 2030), but somewhat more surprisingly, the price of jet fuel also falls by 6 percent. These drops boost diesel fuel use by about 20 percent and ethanol use (E85) by 10 percent in the light-duty vehicle market, which boosts sales of vehicles burning these types of fuels.

The price increase for natural gas results in decreased natural gas use in each of the four other sectors: residential, commercial, industrial, and electricity. The largest drop is in the electricity sector, where use of natural gas is 11 percent lower, dropping from 6.9 quads Btu in 2030 to 6.11 quads Btu, replaced by nuclear, coal, and renewables. There is some minor substitution of natural gas with petroleum-based liquids in all sectors, but the differences in 2030 are trivial.

Fuel Economy and VMT Effects

The bounding scenario features slightly higher fuel economy for the stock of NGVs and lower fuel economy for diesel, because the diesel fleet is so much older than in the base case. By 2030, fuel economy for the stock of diesel and natural gas heavy-duty trucks is 5.8 mpg GGE for diesel (versus 6.5 in the reference case) and 7.4 mpg GGE for NGVs (versus 7.3 in the reference case). Efficiency of new vehicles is, by design, unchanged between the scenario and the reference case.

VMT per truck changes markedly in the bounding scenario. Given high NGV purchase rates and the rapid increase in the stock of NGVs, their average age falls, which raises VMT per truck under the assumption built into NEMS that newer vehicles, being more reliable and having lower maintenance costs, are driven more miles per year. The opposite happens with diesel trucks; as they age, they are driven less. Thus, in the bounding scenario, average VMT per diesel truck falls from 37,000 to 19,000 miles from 2011 to 2030 while average VMT per NG truck rises from 58,000 in 2011 to 69,000 in 2014. From there, the NG stock begins to age, so VMT by

2030 is down to 48,000. Note that these estimates are for both class 7 and 8 vehicles, since NEMS cannot distinguish more finely.

Costs and Cost-Effectiveness

Table 6 shows the welfare costs associated with the LNG truck bounding scenario for the two alternative interest rates (10 percent and 31 percent), three alternative vehicle price differentials, and two alternative elasticities of demand for trucking services (0 and 0.2). At a low LNG truck price—only a \$35,000 price premium over a diesel truck (the most optimistic price projection)—such an LNG penetration scenario generates a welfare cost of \$78 billion using an interest rate of 10 percent. The mandate generates social costs of \$186 billion to \$209 billion for the most reasonable current truck purchase price differential, but the results also suggest that these costs are sensitive to that differential, but not particularly sensitive to the choice of discount rate (or alternatively, to assumptions about market failure versus hidden costs). In terms of cost-effectiveness,⁴¹ Tables 7a. and b. provide reductions in CO₂ and oil use, respectively. Table 8 shows a best cost-effectiveness estimate in terms of CO₂ emissions reductions of about \$76-88/ton, which are quite high. But, the LNG truck mandate/subsidy should be thought of as an oil use reduction policy. Its cost-effectiveness in terms of oil reductions comes in at a very reasonable \$14–\$15 per barrel for what is considered to be the best set of assumptions (Table 9).⁴²

⁴¹ Cost-effectiveness is computed with effectiveness measures that estimate oil consumption reductions and CO₂ reductions out to the end of the last (2030s) cohorts lifetime (2045), assuming that aggregate emissions fall at 1/15th per year. Similarly, the costs in this calculation account for fuel savings for the vehicle purchased in 2030 over the lifetime of the vehicle (until 2045).

⁴² See the full RFF/NEPI report for a cost-effectiveness comparison with other policies.

Table 6. PDV Welfare Costs (Billions \$2007)

	Diesel truck price = \$120K; natural gas reserves in AEO2009					
	LNG truck price = \$155K		LNG truck price = \$190K		LNG truck price = \$220K	
	Interest rate		Interest rate		Interest rate	
Demand elasticity	0.1	0.31	0.1	0.31	0.1	0.31
0	78.7	105.0	191.2	217.5	287.7	314.0
0.2	77.8	103.1	186.4	209.4	277.0	297.0

Table 7a. Cumulative CO₂ Reductions (2010-2030): Original Gas Estimates

Cumulative reductions (mmt)	
Total energy-CO ₂ emissions	1821.00
Total other greenhouse gases	6.08
Total GHG emissions	1827.08

Table 7b. Oil Consumption Reductions

Cumulative reduction (million barrels) 2010–2030	8030.10
Reduction from 2007-2030 (mmbd)	4.13

Table 8. Cost-Effectiveness \$/ton CO₂

	Diesel truck price = \$120K; natural gas reserves in AEO2009					
	LNG truck price = \$155K		LNG truck price = \$190K		LNG truck price = \$220K	
	Interest rate		Interest rate		Interest rate	
Demand elasticity	0.1	0.31	0.1	0.31	0.1	0.31
0	32	43	78	88	117	127
0.2	32	42	76	85	112	120

Table 9. Cost-Effectiveness \$/Barrel Oil

	Diesel truck price = \$120K; natural gas reserves in AEO2009					
	LNG truck price = \$155K		LNG truck price = \$190K		LNG truck price = \$220K	
	Interest rate		Interest rate		Interest rate	
Demand elasticity	0.1	0.31	0.1	0.31	0.1	0.31
0	6	8	14	16	21	23
0.2	6	8	14	15	20	22

Results Using the Reference Case Modified for Enhanced Natural Gas Resources

In this scenario, the same penetration of NG trucks is imposed on a reference case modified for larger natural gas resources, using estimates from the Potential Gas Committee. As expected, in comparing these results to those in the original reference case, natural gas is much cheaper in every year under the modified case. It might be expected that welfare costs would be lower for the natural gas truck scenario with enhanced resources than without enhanced resources because natural gas prices would be lower in the former case. This makes the spread between diesel and LNG fuel prices greater, which itself increases fuel savings. However, this greater spread is already accounted for in the modified reference case, with the welfare costs of the LNG truck scenario based on the difference between the reference case run and the scenario run. Thus, it is an empirical question whether and to what extent welfare costs are lower or higher with and without a world of enhanced shale gas resources.

In fact, welfare costs turn out to be lower with enhanced natural gas resources. More abundant natural gas resources lead to a downward shift in supply. Prices of natural gas rise much more slowly than with the original reference case gas resources assumptions, even given high demand for natural gas when trucks start using this fuel in great numbers. This lower price in turn lowers overall welfare costs.

Table 10 shows welfare costs for the LNG truck scenario with enhanced gas resources. Comparing this table with Table 6, it is apparent that the economics are, indeed, more favorable for LNG trucks when there are larger resources of natural gas, whether we use a discount rate of 10 percent or 31 percent. For instance, our best estimates drop 14 percent, from a welfare cost of \$186 billion over the projection period to \$160 billion. Assuming the optimistic \$35,000 price

differential and discounting at a rate of 10 percent yields the largest percentage drop in welfare costs—35 percent. The smallest drop in welfare costs is around three percent.

The LNG truck scenario actually results in less of a reduction in both CO₂ and oil use than in the AEO2009 gas shale case. This occurs to some degree because the natural gas is cheaper and results in increases in natural gas use throughout the economy, and these changes in the baseline offset some of the CO₂ reductions and oil use (Tables 11a. and b.) when LNG trucks are substituted for diesel trucks. To see this, note that oil use falls (cumulatively) 8 billion barrels over the projection period with the original AEO2009 assumptions and 7.5 billion barrels with the enhanced gas resources assumed. For CO₂, emissions fall by 1.8 billion tons cumulative over the projection period using AEO2009 assumptions and only 1.3 billion tons using the enhanced gas assumptions.

As seen in Tables 12 and 13, with enhanced shale gas resources assumed, our best estimates are for average costs per ton CO₂ reduced of \$66 and per barrel of oil reduced of \$13. These estimates (and others in the tables) can be compared with cost-effectiveness results using the original shale gas resource estimates. With lower costs and lower effectiveness, it is an empirical question whether cost-effectiveness improves or worsens in a world with enhanced gas resources. Compare Tables 8 and 9 to Tables 12 and 13, respectively. For CO₂ emissions, average costs per ton are uniformly lower with enhanced gas resources. The largest percentage difference (25 percent) occurs under the most optimistic investment cost and discount rate assumptions: \$32 per ton (original reference case) versus \$21 per ton (enhanced resources case). For oil, there is little change in either case in average costs per barrel of consumption reduced. In percentage terms, the most optimistic assumption set produces the largest drop in cost per barrel (33 percent, from \$6 per barrel to \$4 per barrel) without and with enhanced shale gas assumed.

Table 10. PDV Welfare Costs (Billions \$2007)

	Diesel truck price = \$120K; natural gas reserves from Potential Gas committee					
	LNG truck price = \$155K		LNG truck price = \$190K		LNG truck price = \$220K	
	Interest rate		Interest rate		Interest rate	
Demand elasticity	0.1	0.31	0.1	0.31	0.1	0.31
0	50.6	94.7	163.9	208	261	305.1
0.2	50.2	92.9	160.2	199.5	251.8	286.9

Table 11a. Cumulative CO₂ Reductions (2010–2030):Enhanced Gas Estimates

Total energy–CO ₂ emissions (mil tons)	1390.58
Total other greenhouse gases	0.65
Total GHG emissions	1391.23

Table 11b. Oil Consumption Reductions

Cumulative reduction (mil barrels) (2010–2030)	7495.81
Reduction from 2007-2030 (mmbd)	3.96

Table 12. Cost-Effectiveness \$/Ton CO₂

	Diesel truck price = \$120K; natural gas reserves in PGC					
	LNG truck price = \$155K		LNG truck price = \$190K		LNG truck price = \$220K	
	Interest rate		Interest rate		Interest rate	
Demand elasticity	0.1	0.31	0.1	0.31	0.1	0.31
0	21	39	68	86	108	126
0.2	21	39	66	83	104	119

Table 13. Cost-Effectiveness \$/Barrel Oil

	Diesel truck price = \$120K; natural gas reserves in PGC					
	LNG truck price = \$155K		LNG truck price = \$190K		LNG truck price = \$220K	
	Interest rate		Interest rate		Interest rate	
Demand elasticity	0.1	0.31	0.1	0.31	0.1	0.31
0	4	8	13	17	21	24
0.2	4	7	13	16	20	23

Conclusions

LNG trucks can, under certain conditions, be a good deal for society in reducing oil and CO₂ emissions with reasonably competitive cost-effectiveness.^{43,44} Recent expansion of shale gas resource estimates does not, in general, relax these conditions. The fact that such trucks have not yet made significant inroads stems in part from demand for rapid payback of the high up-front costs of LNG trucks, but fuel price differentials and investment cost differentials are more important. Probably even more important is the lack of LNG fueling infrastructure—the chicken and egg problem discussed above—and concerns about safety. The interstate trucking industry is moving increasingly from a long-haul route structure to a “hub and spoke” structure, a development that could mean fewer stations are needed (Taylor, DuCote, and Whicker, 2006) to solve the chicken and egg problem.⁴⁵

Note, however, that even if the trucking industry had adequate NG infrastructure for long-haul trucking, there might still be economic issues concerning lack of infrastructure appropriate to the truck resale market. Trucks are sometimes taken out of the commercial trucking business and resold for use on farms and within cities after six to eight years of use. Without adequate NG infrastructure in rural and urban areas, this market could fail, effectively limiting the useful life of these trucks, both from a private and social perspective.

As for safety concerns, there are arguments on both sides, with proponents suggesting that the need to contain high pressures and keep temperatures low requires extremely robust tanks and other equipment that actually make such trucks safer in an accident than their diesel counterparts. Opponents refer to concerns about LNG storage facilities and their explosive potential. An independent review of safety concerns (Hesterberg, Bunn, and Lapin 2009) finds that diesel buses have a “significant fire and safety advantage over CNG vehicles [buses].”

⁴³ TIAX (2005) assessed the future life-cycle costs (LCC) of owning, operating, and maintaining comparable emission diesel and natural gas heavy-duty engines for refuse haulers, transit buses, and short-haul trucks. These costs are not significantly different across fuel type. After 2010, LCCs for natural gas vehicles are lower when oil prices are greater than \$31 per barrel (2005\$). Note that a 5 percent discount rate was used for these calculations.

⁴⁴For analyses of cost-effectiveness of CNG buses, see Cohen (2005) and Cohen, Hammitt, and Levy (2003)

⁴⁵ . See <http://scm.ncsu.edu/public/lessons/less031014.html> for a discussion of this system for major retailers in the United States. An interesting presentation by DHL (DHL FHWA Net Conference, October 20, 2004) to reconfigure their centralized system to hub and spoke can be found at www.fhwa.dot.gov/download/hep/freightplanning/talkingfreight10_20_04hp.ppt.

Whether these conclusions would hold for LNG versus diesel trucks is unclear. A government source⁴⁶ focusing on CNG *versus* LNG concludes that the latter is less corrosive but cannot take an odorant, so leaks could go undetected longer, requiring methane detectors. With respect to LNG, the very cold temperatures mean that the storage systems require intensive monitoring for build-up of pressure in the tanks, so the gas can be vented. While the report says that rupturing of the tanks is extremely unlikely, it also says that any resulting fire will release 60 percent more heat than from an “equivalent” gasoline tank rupture. Refueling the vehicle requires precautions as well and the rapid change in temperature can stress materials. The industry’s response to these points is basically that the fuel is safe if the proper procedures are followed.

In any event, a variety of developments are in play to make LNG vehicles economical even without subsidies on the fuel or the vehicles. Natural gas prices may remain relatively low given vast new amounts of shale becoming available. This means that even if a large new demand for such gas develops, price increases may be moderate, perhaps more moderate than we forecast in NEMS–RFF. In addition, technological changes are likely to be more rapid on the natural gas vehicle side, because diesel vehicle technologies have been in development for so long, helping to pushing vehicle price differentials down. Third, if demand for NG trucks does increase, economies of scale could further reduce prices of LNG trucks. Fourth, diesel vehicles may become disadvantaged in the future by a carbon policy and with increasingly stringent air pollution regulations. In summary, the use of natural gas in transportation—particularly in heavy-duty trucks—remains something worthy of significantly more attention.

⁴⁶ <http://www.chebeague.org/fairwinds/risks.html>, which is an excerpt from a report produced by the Federal Transit Administration’s Clean Air Program, Section 3.3.4 Liquified Natural Gas.

Appendix A

NEMS DOCUMENTATION

Freight Truck Assumptions

Although the language below is verbatim from the U.S. Energy Information Agency's documentation,⁴⁷ note that penetration of CNG trucks is not modeled in NEMS, but is incorporated by assumption only.

“The freight truck module estimates vehicle stocks, travel, fuel efficiency, and energy use of three size classes: light medium (Class 3), heavy medium (Classes 4–6), and heavy (Classes 7–8). Within the size classes, the stock model structure is designed to cover twenty vehicle vintages and to estimate energy use by four fuel types: diesel, gasoline, liquefied petroleum gas, and CNG. Fuel consumption estimates are reported regionally (by Census Division) according to the distillate fuel shares from the State Energy Data Report. The technology input data specific to the different types of trucks including the year of introduction, incremental fuel efficiency improvement, and capital cost of introducing the new technologies.

The freight module uses projections of dollars of industrial output to estimate growth in freight truck travel. The industrial output is converted to an equivalent measure of volume output using freight adjustment coefficients. These freight adjustment coefficients vary by North American Industrial Classification System (NAICS) code with the deviation diminishing gradually over time toward parity. Freight truck load-factors (ton-miles per truck) by NAICS code are constants formulated from historical data.

Fuel economy of new freight trucks depends on the market penetration of various emission control technologies and advanced technology components.¹ For the advanced technology components, market penetration is determined as a function of technology type, cost effectiveness, and introduction year. Cost effectiveness is calculated as a function of fuel price, vehicle travel, fuel economy improvement, and incremental capital cost. Emissions control equipment is assumed to enter the market to meet regulated emission standards.

Heavy truck freight travel is estimated by class size and fuel type based on matching projected freight travel demand (measured by industrial output) to the travel supplied by the

⁴⁷ www.eia.doe.gov/oiaf/aso/assumption/transportation.html (2009).

current fleet. Travel by vintage and size class is then adjusted so that total travel meets total demand. Initial heavy vehicle travel, by vintage and size class, is derived using Vehicle Inventory and Use Survey (VIUS) data.

Initial freight truck stocks by vintage are obtained from R. L. Polk Co. and are distributed by fuel type using VIUS data. Vehicle scrappage rates are also estimated using R. L. Polk Co. data.

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