SOUTHERN CALIFORNIA
ASSOCIATION of GOVERNMENTS

Comprehensive Regional Goods Movement Plan and Implementation Strategy

Task 10.2 Evaluation of Environmental Mitigation Strategies

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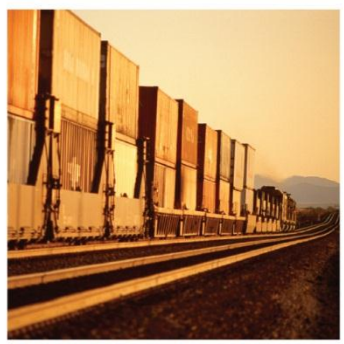
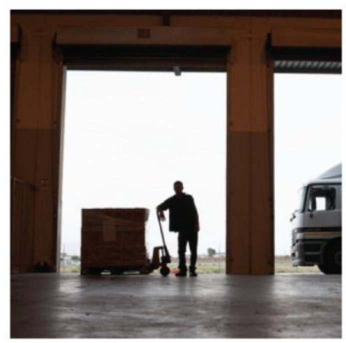
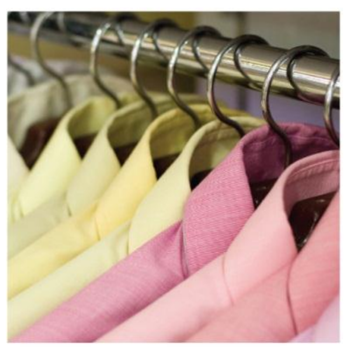
SOUTHERN CALIFORNIA DELIVERS THE GOODS







SCAG Comprehensive Regional Goods Movement Plan and Implementation Strategy

Task 10.2
Evaluation of Environmental Mitigation Strategies

April 2012

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The Southern California Association of Governments

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1. Introduction

This report presents an evaluation of strategies to reduce the environmental impacts of heavy-duty trucks and railroad locomotives in the SCAG region. The bulk of the report focuses on air pollutant emissions, with shorter sections discussing non-air environmental impacts (noise, vibration, and visual impacts). Most of existing research addresses technologies to reduce emissions from the truck and locomotive fleets as they exist today or in the near future. In contrast, there is relatively little information on the effectiveness, cost, and implementation mechanisms for emission reduction strategies that would be relevant for the Southern California truck and locomotive fleets as they will be 15 to 25 years from now. The primary purpose of this report is to describe environmental mitigation options to consider for inclusion in SCAG's Comprehensive Regional Goods Movement Plan and 2012 Regional Transportation Plan. All strategies in this report were analyzed with the purpose of better understanding options to reduce emissions and other environmental impacts from goods movement sources. Issues such as the operational impacts of technology strategies and legal authority for implementation are generally not analyzed in this report.

In Southern California, goods movement and air quality are inextricably linked. Much of the SCAG region (and nearly all of the urbanized areas) does not meet federal ozone and fine particulate (PM2.5) air quality standards. Goods movement is a major source of emissions that contribute to these regional air pollution problems. Goods movement can also cause localized air pollution "hot spots" that can have adverse human health impacts.

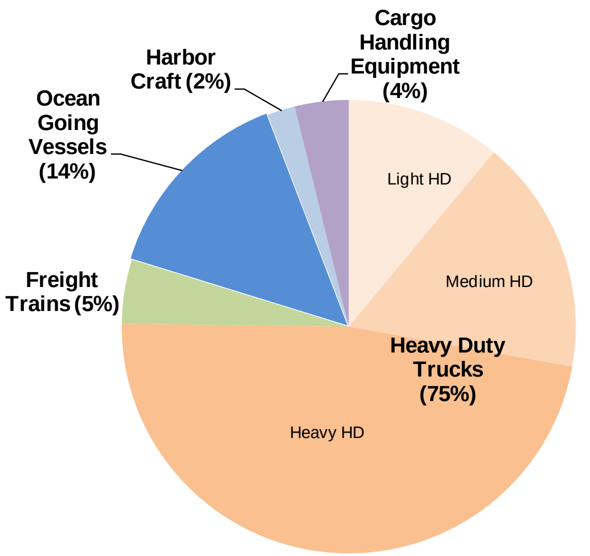
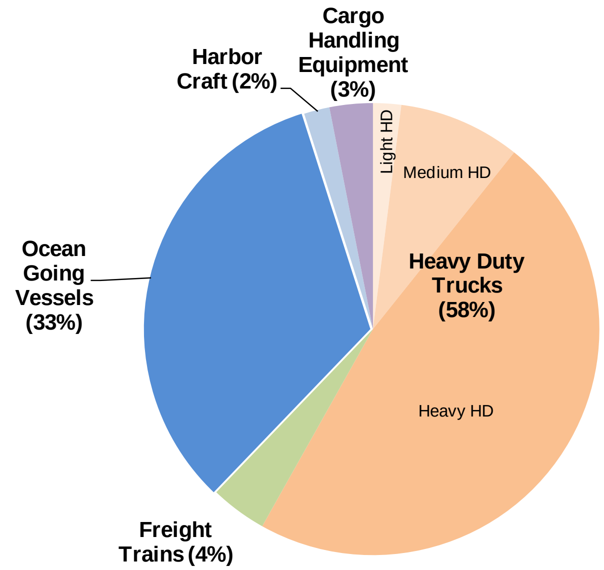
The two air pollutants of greatest concern in Southern California are nitrogen oxides (NOx) and fine particulate matter. NOx is a major component in the formation of ground level ozone, or smog. (Goods movement is a relatively minor source of the other major smog precursor, volatile organic compounds.) Ground level ozone can trigger a variety of health problems including aggravated asthma, reduced lung capacity, and increased susceptibility to respiratory illnesses like pneumonia and bronchitis. The South Coast Air Basin is classified as an Extreme nonattainment area for the federal ambient ozone standard, with a required attainment date of 2023. Most of the rest of the SCAG region is also in nonattainment for the federal ozone standard, including Ventura County, Imperial County, the Coachella Valley, the Antelope Valley, and the western parts of the Mohave Desert.

Fine particulate matter is directly emitted from diesel engines and is produced by motor vehicle tire and brake wear. PM2.5 is also created when emissions of NOx or sulfur oxides (SO_X) react with other compounds in the atmosphere to form particles. Many scientific studies have linked breathing PM to significant health problems, including aggravated asthma, chronic bronchitis, and heart attacks. The South Coast Air Basin (SCAB) is a PM2.5 nonattainment area with a required attainment date of 2015; a portion of Imperial County is also in nonattainment for PM2.5. Aside from regional particulate standards, PM2.5 can form localized concentrations, or "hot spots", especially in areas of heavy goods movement activity.

Diesel particulate matter is of particular concern because it is widely believed to be a human carcinogen when inhaled. AQMD's MATES-III study found that 70% of the air pollution inhalation cancer risk in the region was caused by diesel particular matter, most of which comes from goods movement sources.

Exhibit 1-1 shows the current sources of goods movement emissions. Heavy-duty trucks contribute 75% of the NOx emissions and 58% the PM2.5 emissions from goods movement. Freight trains contribute 4-5% of goods movement emissions.

Exhibit 1-1: Goods Movement NOx and PM2.5 Emissions in SCAB by Source, 2010

NOx **Emissions**	**PM2.5 Emissions**
	

Source: ICF analysis based on EMFAC 2007 (modified for recession effects), ARB regulatory documents for marine fuel requirements, ARB emission inventory, ARB Goods Movement Plan, ARB and U.S. EPA locomotive analyses.

Goods movement is also a major source of greenhouse gas (GHG) emissions that contribute to global climate change. Although reduction in GHG emissions from goods movement is not required under SB 375 (which focuses solely on light-duty vehicle emissions), the state has established GHG reduction goals under AB 32, as have a number of local governments. The Regional Goods Movement Plan should support these state and local efforts.

The remainder of this report focuses primarily on truck and locomotive emissions, since SCAG is actively engaged in planning improvements to highway and railroad systems. These activities are occurring in parallel to efforts by ARB and U.S. EPA, who are actively working to reduce emissions from trucks and locomotives. Ships and other marine vessels are also major contributors to Southern California air quality problems; these emissions sources are being actively addressed through actions by the ports, ARB, and U.S. EPA.

Section 2 of the report presents an overview of the heavy-duty truck population, key regulations affecting truck emissions, and a baseline projection of truck emissions in the South Coast Air Basin (SCAB) and entire SCAG region for 2023 and 2035. The baseline emissions estimates were developed using a modified version of the EMFAC2007 model. The California Air Resources Board (ARB) is currently updating EMFAC, but the new version is not expected to be available for use in SCAG's Comprehensive Regional Goods Movement Plan development. Therefore, ICF used information from ARB to modify the EMFAC2007 model to account for the economic recession, which has caused a drop in truck activity and emissions, and the Statewide Truck and Bus Rule, which will significantly reduce emissions from existing (in-use) trucks over the next decade.

Section 3 of the report presents a detailed assessment of advanced truck technologies to reduce emissions. Conventional truck emission reduction strategies, such as exhaust retrofits and engine replacement (repower), will be largely ineffective by 2020 due to fleet turnover and the introduction of trucks that meet the stringent U.S. EPA 2010 emission standards. The Regional Goods Movement Plan Steering

Committee and other stakeholders have expressed a strong interest in advanced technologies to achieve a low- or zero-emission goods movement system. This section discusses four categories of advanced truck technologies: advanced natural gas vehicles, hybrid-electric vehicles, plug-in hybrid electric vehicles, and battery electric vehicles. For each category, the report describes the current state of technology, expected developments over the next 10-20 years, and barriers to advancement. The report presents estimates of the expected emissions benefit, incremental vehicle cost, and timeframe for commercial availability for each technology and truck weight class. The section concludes with a presentation of hypothetical scenarios for deployment of these emission reduction technologies, including region-wide emissions benefits and costs.

Section 4 presents an overview of the locomotive population, key regulations affecting locomotive emissions, and a baseline projection of locomotive emissions in the South Coast Air Basin (SCAB). ICF's assumptions used to develop these baseline projections are currently being reviewed by the railroads and ARB, and therefore the emissions estimates are subject to change.

Section 5 describes strategies to reduce emissions from locomotives in 2023 and 2035. The report quantifies the benefits and costs of strategies to reduce line haul locomotive emissions (acceleration of Tier 4 locomotives and railroad main line electrification) and strategies focused on switchers, and also discusses a number of additional strategies that are not quantified.

Section 6 discusses strategies that could reduce emissions by changing the operation or maintenance of trucks. Section 7 describes non-air environmental impacts (noise, vibration, visual) of goods movement and reviews mitigation strategies.

2. Truck Emissions Baseline

This section discusses the trucking sector, key regulations affecting truck emissions, and emissions under a baseline (business-as-usual) scenario to 2035.

2.1. Introduction

Trucks perform the bulk of goods movement in Southern California, ranging from full truckload shipments to local delivery of small parcels. Trucks comprise a wide variety of body types and sizes, which makes a concise summary of this sector difficult. In terms of VMT and ton-miles, the most common truck is the 5-axle tractor-trailer combination truck, used to move a trailer or shipping container on a chassis. This is the vehicle that the public typically considers to be the "trucking sector." However, from an air quality perspective, it is important to recognize that other truck types contribute significantly to regional emissions. According to ARB's EMFAC model (as presented in Section 2.3), smaller single-unit trucks are responsible for more than one-third of all NOx emission from trucks and nearly 20% of PM2.5 emissions from trucks.

ARB and South Coast AQMD use three categories of heavy-duty vehicles based on gross vehicle weight rating (GVWR), shown in Exhibit 2-1, with the light heavy-duty (LHD) category sometimes split into LHD1 and LHD2

Exhibit 2-1. Heavy-Duty Vehicle Classes

Description of Vehicle		Weight Class (lbs)
Light heavy-duty trucks (LHD)	1	8,501-10,000
	2	10,001-14,000
Medium heavy-duty trucks (MHD)		14,001-33,000
Heavy heavy-duty trucks (HHD)		33,001-80,000

Exhibit 2-2 shows some examples of trucks in each of the ARB weight classes, along with their commercial classification (Class 2b – Class 8). For regional air quality planning purposes, emissions are reported for all heavy-duty vehicles. However, HDVs include vehicles that are, strictly speaking, not engaged in the movement of goods, such as utility trucks, large tow trucks, and even large SUVs.

Exhibit 2-2. Examples of Truck by Class

ARB Weight Class	Examples			
Light Heavy-Duty	Class 2b 8,501-10,000 lbs		Class 3 10,001-14,000 lbs	
Medium Heavy-Duty	Class 4 14,001-16,000 lbs		Class 5 16,001-19,500 lbs	
	Class 6 19,501-26,000 lbs		Class 7 26,001-33,000 lbs	
Heavy Heavy-Duty	Class 8a 33,001-60,000 lbs		Class 8b > 60,000 lbs	

2.2. Key Truck Regulations

Emissions from heavy-duty trucks are affected by both federal and California regulations. The first U.S. EPA emissions standards for heavy-duty trucks took effect in 1988. The current standards took effect fully in 2010. Model year 2010 and newer trucks must comply with these standards:

- PM: 0.01 grams/brake horsepower-hour (g/bhp-hr)
- NOx: 0.20 g/bhp-hr
- NMHC: 0.14 g/bhp-hr

These standards reflect a 90% or greater reduction in emissions as compared to the standards in effect for model years 2006 and earlier. ARB also has the authority to regulate emissions from new motor vehicles sold in California. ARB's emissions standards for new heavy-duty vehicles have been identical to the U.S. EPA standards for more than a decade. Exhibit 2-3 shows how truck emission standards have changed over time.

Exhibit 2-3: EPA Emission Standards for Heavy-Duty Trucks (g/bhp-hr)

Model Year	NOx	PM
1988-89	10.7	0.6
1990	6.0	0.6
1991-93	5.0	0.25
1994-97	5.0	0.1
1998-2003	4.0	0.1
2004-2006 [a,b]	2.0	0.1
2007	2.0	0.01
2010 [c]	0.2	0.01

Note a: Under a consent decree with U.S. EPA, engine makers implemented the 2004 standards in October 2002.
Note b: Standards allow the option of 2.4 g/bhp-hr NMHC+NOx, or 2.5 g/bhp-hr NMHC+NOx and 0.5 NMHC.
Note c: NOx standards are phased-in 2007-2010; most 2007-2009 engines meet a 1.1 g/bhp-hr NOx standard.

Several other state and federal standards will affect truck emissions in the coming years, as summarized below.

Truck and Bus Rule (California)

On December 12, 2008, ARB approved the statewide in-use truck and bus rule, the most far-reaching diesel emission regulation in the state's history. Unlike EPA emissions standards, the ARB rule applies to existing vehicles already on the road. The rule targets most in-use trucks in the state over 14,000 lbs GVWR (i.e., MHD and HHD trucks).

The regulation calls for the phase-in of best available control technology (BACT) for PM and NOx between 2011 and 2023. There are special provisions that can delay the clean-up requirements (e.g., for small fleet owners and owners of agricultural vehicles); however, by 2023 all heavy-duty diesel vehicles must have a 2010 model year engine or equivalent.

Heavy-Duty Truck Greenhouse Gas Regulation (California)

The heavy-duty truck greenhouse gas regulation requires improved fuel efficiency of tractors that pull 53-foot or longer box-type trailers. The fuel efficiency gains will be achieved by improving the aerodynamics of sleeper-cab tractors and box-type trailers, and by using low rolling resistance tires. The program requires installation of technologies verified by EPA's SmartWay Transport Partnership Program. For new vehicles, beginning with the 2011 model year, all sleeper-cab tractors must be SmartWay certified. The legislation calls for older trailers to be retrofitted with SmartWay verified technologies from 2010 to 2015 for large fleets and 2013 to 2015 for small fleets.[1] SmartWay verified technologies including low rolling resistance tires and aerodynamic technologies such as trailer rear fairings, front gap fairings, and side skirts.

[1] The regulation defines a large fleet as any fleet operating 21 or more trailers in California; fleets with 20 or fewer trailers are small fleets.

Truck Idling Limit (California)

As of January 1, 2008, all diesel-fueled trucks with a GVWR greater than 10,000 pounds are prohibited to idle for more than 5 minutes when stopped within California's borders. This regulation applies to both day cabs and trucks with sleeper berths. Model year 2008 and newer sleeper berth trucks are required to be equipped with a non-programmable engine shutdown system that automatically turns off the engine after five minutes of idling (or optionally meet a stringent NOx idling emission standard). Day cab trucks and pre-2008 sleeper berth trucks must manually shut down engines. The regulation also sets emission performance requirements for technologies such as diesel-fueled auxiliary power systems (APS) and fuel-fired heaters that are used for cab temperature control.

Low Carbon Fuel Standard (California)

The Low Carbon Fuel Standard (LCFS) was enacted by executive order S-1-07 and requires at least a 10% reduction of the carbon intensity of transportation fuels by 2020. The LCFS is identified as an early action item by ARB in the implementation of the Global Warming Solutions Act (AB 32). The standard is applied to fuels on a lifecycle basis, which includes upstream emissions from production, refining, transportation, and in-use (i.e., tailpipe) emissions.

Heavy-Duty Vehicle Fuel Economy and GHG Standards (United States)

The EPA and National Highway Traffic Safety Administration (NHTSA) has adopted fuel economy and GHG standards for medium- and heavy-duty vehicles, including all on-road vehicles rated at gross vehicle weight at or above 8,500 lbs, and the engines that power them. The standards cover model years 2014-2018. The standards are defined using two types of metrics: 1) grams per mile (or gallons per 100 miles) for pickups and vans, and 2) grams per ton-mile (or gallons per 1000 ton-miles) for vocation vehicles and combination tractors. The standards for the three main regulatory categories are summarized here.

Combination Tractors. This category focuses on vehicles that pull trailers or containers. The standards (see Exhibit 2-4) also vary by the tractor roof height, which is selected by operators based on the type of trailer being hauled.

Exhibit 2-4. MY 2017 Combination Tractor Standards

	EPA Emission Standards (gCO2 / ton-mile)			NHTSA Fuel Consumption Standards (gallon/1,000 ton-mile)		
	Low Roof	Mid Roof	High Roof	Low Roof	Mid Roof	High Roof
Day Cab, Class 7	103	103	116	10.1	10.1	11.4
Day Cab, Class 8	78	78	86	7.7	7.7	8.5
Sleeper Cab, Class 8	64	69	71	6.3	6.8	7.0

Source: EPA/NHTSA Regulatory Announcement, EPA/OTAQ, EPA-420-F-10-901, October 2010

Heavy-Duty Pickup Trucks and Vans. EPA and NHTSA have proposed to set corporate average standards for heavy-duty pickup trucks and vans, similar to the approach used to regulate light-duty vehicles. The standard that each manufacturer must meet will depend on the sales mix, and differentiates vehicles depending on their "work factor" – a combination of a vehicle's payload, towing capabilities, and whether or not the vehicle has 4-wheel drive.

Vocational Vehicles. Vocational vehicles include the broadest range of truck and bus types, including delivery, refuse, and utility trucks, as well as transit or shuttle buses. Due to the way vehicles are built, both EPA and NHTSA have proposed regulating chassis manufacturers. The proposed standards are shown in Exhibit 2-5.

Exhibit 2-5 MY 2017 Vocational Vehicle Standards

	EPA	NHTSA
	Full Useful Life Emissions Standards (g CO2/ton-mile)	Fuel Consumption Standards (gal/1,000 ton-mile)
Class 3-5	344	33.8
Class 6-7	204	20.0
Class 8	107	10.5

Source: EPA/NHTSA Regulatory Announcement, EPA/OTAQ, EPA-420-F-10-901, October 2010

2.3. Baseline Truck Emissions to 2035

Regional estimates of vehicle emissions in California are typically developed using ARB's EMFAC model. The version of the model currently available is EMFAC2007; an updated version of EMFAC is expected to be released sometime in 2011. Without modification, EMFAC2007 is inadequate to estimate current and future truck emissions because of several changes that have occurred since the model's release.

One change is the economic recession, which has caused a drop in truck activity and emissions. The other is the adoption of the Statewide Truck and Bus Rule, which will significantly reduce emissions from existing (in-use) trucks over the next decade. The rule was promulgated by ARB in December 2008 and recently amended in December 2010. It essentially requires that all pre-2010 trucks over 14,000 lbs gross vehicle weight rating (GVWR) be replaced with trucks meeting the 2010 emissions standards by 2023.[2]

To develop an estimate of truck emissions to 2035, we adjusted EMFAC2007 to account for these two changes. This section describes these adjustments and the results.

Methodology

Impacts of Recession

The recent recession caused a reduction in both truck VMT and truck sales, which has resulted in a major, real-world reduction in truck emissions on the order of 20%. However, not all trucking sectors have been affected equally. ARB estimates that the recession will have a lasting impact on trucking activity in California through 2023.[3]

Because of these impacts, the EMFAC model growth factors for MHD trucks (14,000 – 33,000 lbs GVWR) and HHD trucks (greater than 33,000 lbs GVWR) should be depressed starting in 2007. ARB has developed adjusted factors for truck growth to be applied to EMFAC2007 growth rates for MHD and HHD trucks.[4] We used these factors to adjust truck populations for both the South Coast Air Basin (SCAB) and the SCAG counties (see Appendix A). We did not adjust populations of LHD1 trucks (8500 – 10,000 lbs GVWR) and LHD2 trucks (10,000 – 14,000 lbs GVWR) from those provided in EMFAC.

[2] Air Resources Board, "Truck and Bus Regulation Compliance Requirements Summary", Fact Sheet, March 23, 2011. Available at http://www.arb.ca.gov/msprog/onrdiesel/documents/FSRegSum.pdf.

[3] K. Jaw and T. Sax, "Impact of the Economic Recession on Truck and Bus Emissions in California," presented at the 21st Annual CRC On-Road Vehicle Emissions Workshop, San Diego, March 21-23, 2011.

[4] See http://www.arb.ca.gov/msprog/onrdiesel/1085/supporting_files/growth_and_sales/growth_w_recession.xls

Impacts of In-Use Truck and Bus Rule

The Truck and Bus Rule applies to nearly all diesel-fueled trucks with a GVWR greater than 14,000 pounds that are privately- or federally-owned, as well as privately- and publicly-owned school buses. Other public fleets, such as solid waste collection trucks and transit buses, are already subject to other regulations and are not affected by the Truck and Bus Rule. Trucks that transport marine containers must comply with ARB's Drayage Truck Rule. The replacement schedule in the amended regulations is shown in Exhibit 2-6. Lighter trucks are defined as 14,000 to 26,000 lbs GVW while heavier trucks are over 26,000 lbs GVW.

Exhibit 2-6: Implementation Schedule for Truck Replacements

Lighter Trucks (14,000 – 26,000 lbs GVW)		Heavier Trucks (Over 26,000 lbs GVW)	
Engine Year	Replacement Date	Engine Year	Requirements
1995 and older	January 1, 2015	Pre-1994	No requirements until 2015, then 2010 engine
1996	January 1, 2016	1994-1995	No requirements until 2016, then 2010 engine
1997	January 1, 2017	1996-1999	PM filter from 2012 to 2020, then 2010 engine
1998	January 1, 2018	2000-2004	PM filter from 2013 to 2021, then 2010 engine
1999	January 1, 2019	2005-2006	PM filter from 2014 to 2022, then 2010 engine
2003 and older	January 1, 2020	2007-2009	No requirements until 2023, then 2010 engine
2004-2006	January 1, 2021	2010	Meets final requirements
2007-2009	January 1, 2023		

The rule mandates that by 2023, all pre-2010 trucks with GVW over 14,000 lbs will be replaced with 2010+ model year trucks. It is not certain what actual model year truck will serve as the replacement. To develop estimate of possible replacements, we used ARB's analysis of the Truck and Bus Rule to determine the age distribution of MHD and HHD trucks for the SCAB.[5] In other words, we adjust the EMFAC model so that all pre-2010 trucks are eliminated by 2023 and replaced with trucks of model year 2010 – 2022. See Appendix A for the replacement distribution.

Low Carbon Fuel Standard

The Low Carbon Fuel Standard requires at least a 10% reduction of the carbon intensity of transportation fuels by 2020. The standard is applied to fuels on a lifecycle basis, which includes upstream emissions from production, refining, transportation, and in-use (i.e., tailpipe) emissions. We account for this regulation, we adjusted fuel carbon intensity values for 2023 and 2035.

Results – South Coast Air Basin Inventory

Exhibit 2-7 shows 2010 emissions in the South Coast Air Basin by vehicle weight class and fuel type. These estimates were developed using EMFAC 2007 and applying recession adjustment factors from ARB (see Appendix A). The GHG emissions are reported on a lifecycle basis, using modified fuel use estimates from EMFAC and carbon intensity values for gasoline and diesel (reported as grams of carbon dioxide equivalents per unit of energy, g CO2eq/MJ).

[5] See http://www.arb.ca.gov/msprog/onrdiesel/1085/ei_models_recession_proposed.zip

Exhibit 2-7: Heavy-Duty Vehicle Emissions, South Coast Air Basin, 2010

Vehicle Class	Fuel	Pop	VMT (10^6)	Tons per day							
				NOx	PM2.5			PM10			GHGs
					Exh	T&B	Total	Exh	T&B	Total	
LHD1	G	132,775	6.278	15.094	0.063	0.058	0.121	0.068	0.169	0.238	6,495
	D	28,281	1.478	8.371	0.049	0.014	0.063	0.053	0.04	0.093	1,077
	All	161,056	7.756	23.465	0.112	0.072	0.184	0.121	0.209	0.331	7,572
LHD2	G	27,991	1.283	2.96	0.013	0.012	0.025	0.014	0.035	0.049	1,326
	D	21,461	0.984	6.942	0.044	0.009	0.053	0.047	0.027	0.074	731
	All	49,452	2.267	9.902	0.057	0.021	0.078	0.061	0.062	0.123	2,058
MHD	G	19,814	0.922	4.795	0.012	0.008	0.02	0.013	0.025	0.038	1,029
	D	69,699	4.491	46.039	1.067	0.042	1.108	1.16	0.121	1.281	9,835
	All	89,513	5.413	50.834	1.079	0.05	1.128	1.173	0.146	1.319	10,864
HHD	G	3,723	0.329	5.656	0.007	0.005	0.012	0.007	0.014	0.023	409
	D	39,637	7.385	137.785	5.966	0.171	6.138	6.485	0.523	7.008	20,569
	All	43,360	7.714	143.441	5.973	0.176	6.15	6.492	0.537	7.031	20,978
All HD	G	184,303	8.812	28.505	0.095	0.083	0.178	0.102	0.243	0.348	9,260
	D	159,078	14.338	199.137	7.126	0.236	7.362	7.745	0.711	8.456	32,212
	All	343,381	23.150	227.642	7.221	0.319	7.54	7.847	0.954	8.804	41,472

G = Gasoline; D = Diesel; Exh = Exhaust; T&B = Tire and Brake emissions

To estimate the SCAB area inventory for 2023, we first determined MHD and HHD truck populations using EMFAC 2007. We applied the recession adjustment factors from ARB (see Appendix A) to model years 2007 – 2023 trucks. We calculated the population age fractions by dividing a given model year population by the total of all trucks in a given category (MHD or HHD). We summed the population age fractions for pre-2010 trucks and redistributed this population to model year 2010+ trucks, based on ratios suggested by ARB. This provided new age distribution fractions for model years 2010+. See Appendix A for the calendar year 2023 truck populations by model year for the SCAB.

Exhibit 2-8 shows emissions calculated for the South Coast Air Basin in 2023.

Exhibit 2-8: Heavy-Duty Vehicle Emissions, South Coast Air Basin, 2023

Vehicle Class	Fuel	Pop	VMT (10^6)	Tons per day							
				NOx	PM2.5			PM10			GHGs
					Exh	T&B	Total	Exh	T&B	Total	
LHD1	G	170,711	7.560	11.835	0.088	0.070	0.158	0.095	0.205	0.300	7,101
	D	40,031	1.782	4.537	0.043	0.017	0.060	0.047	0.049	0.095	1,167
	All	210,742	9.342	16.372	0.131	0.087	0.218	0.142	0.254	0.395	8,268
LHD2	G	35,681	1.581	2.271	0.018	0.014	0.032	0.019	0.043	0.062	1,483
	D	26,756	1.168	3.098	0.029	0.011	0.04	0.031	0.031	0.063	768
	All	62,437	2.749	5.369	0.047	0.025	0.072	0.05	0.074	0.125	2,251
MHD	G	23,706	1.162	2.059	0.016	0.011	0.026	0.017	0.031	0.048	1,093
	D	83,434	6.199	7.428	0.566	0.058	0.623	0.615	0.168	0.783	11,737
	All	107,140	7.361	9.487	0.582	0.069	0.649	0.632	0.199	0.831	12,830
HHD	G	1,980	0.154	1.724	0.003	0.003	0.006	0.003	0.007	0.010	160
	D	49,207	12.741	43.202	1.361	0.296	1.657	1.48	0.902	2.382	30,340
	All	51,187	12.895	44.926	1.364	0.299	1.663	1.483	0.909	2.392	30,500
All HD	G	232,078	10.457	17.889	0.125	0.098	0.222	0.134	0.286	0.420	9,837
	D	199,428	21.890	58.265	1.999	0.382	2.380	2.173	1.150	3.323	44,012
	All	431,506	32.347	76.154	2.124	0.480	2.602	2.307	1.436	3.743	53,849

G = Gasoline; D = Diesel; Exh = Exhaust; T&B = Tire and Brake emissions

To estimate 2035 emissions, we applied a similar approach except the recession factors were not applied, on the assumption that the effects of the recession will have dissipated by 2035. The Truck and Bus Rule effects were used to adjust the population of pre-2010 trucks. See Appendix A for the calculated 2035 truck population by model year. Exhibit 2-9 shows calculated truck emissions in the SCAB for 2035.

Exhibit 2-9: Heavy-Duty Vehicle Emissions, South Coast Air Basin, 2035

Vehicle Class	Fuel	Pop	VMT (10^6)	Tons per day							
				NOx	PM2.5			PM10			GHGs
					Exh	T&B	Total	Exh	T&B	Total	
LHD1	G	202,353	8.926	11.033	0.104	0.083	0.187	0.112	0.241	0.354	8,584
	D	47,105	2.065	3.044	0.041	0.019	0.06	0.045	0.056	0.101	1,352
	All	249,458	10.991	14.077	0.145	0.102	0.247	0.157	0.297	0.455	9,936
LHD2	G	42,638	1.883	2.069	0.021	0.017	0.038	0.022	0.051	0.073	1,813
	D	31,358	1.371	1.883	0.026	0.013	0.038	0.028	0.037	0.065	898
	All	73,996	3.254	3.952	0.047	0.03	0.076	0.05	0.088	0.138	2,711
MHD	G	28,498	1.385	1.42	0.019	0.013	0.032	0.02	0.037	0.058	1,327
	D	108,775	6.655	9.227	0.762	0.061	0.823	0.828	0.18	1.008	12,609
	All	137,273	8.040	10.647	0.781	0.074	0.855	0.848	0.217	1.066	13,936
HHD	G	1,488	0.155	1.138	0.003	0.003	0.005	0.003	0.007	0.01	157
	D	72,446	15.468	58.178	1.804	0.359	2.164	1.961	1.095	3.056	36,926
	All	73,934	15.623	59.316	1.807	0.362	2.169	1.964	1.102	3.066	37,083
All HD	G	274,977	12.349	15.66	0.147	0.116	0.262	0.157	0.336	0.495	11,881
	D	259,684	25.559	72.332	2.633	0.452	3.085	2.862	1.368	4.23	51,785
	All	534,661	37.908	87.992	2.78	0.568	3.347	3.019	1.704	4.725	63,666

G = Gasoline; D = Diesel; Exh = Exhaust; T&B = Tire and Brake emissions

Exhibits 2-10, 2-11, and 2-12 illustrate the projected change in SCAB heavy-duty vehicle NOx, PM2.5, and GHG emissions over time. NOx emissions will drop 67% between 2010 and 2023. By 2023, nearly all trucks will comply with the most stringent existing emissions standards, and emissions will then slowly rise due to VMT growth. HDV NOx emission in 2035 will still be 61% below current levels. Similarly, PM2.5 emissions will drop 65% between 2010 and 2023, then rise slightly by 2035. GHG emissions are set to increase in each heavy-duty truck sector due to VMT growth, despite reductions attributable to the Low Carbon Fuel Standard. The GHG emissions are set to increase from current levels by 30% in 2023 and nearly 54% in 2035; the majority of both increases is attributable to HHDVs.

Exhibit 2-10: Heavy-Duty Vehicle NOx Emissions, South Coast Air Basin

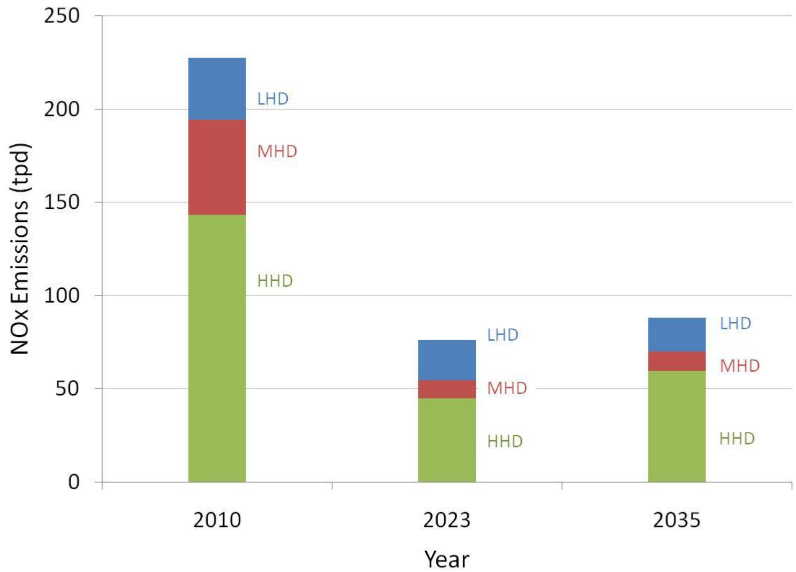


Exhibit 2-11: Heavy-Duty Vehicle PM2.5 Emissions, South Coast Air Basin

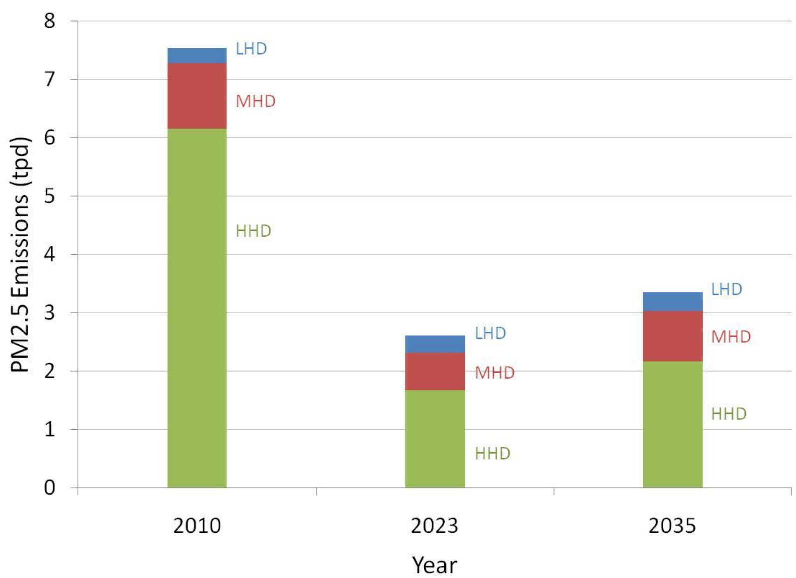
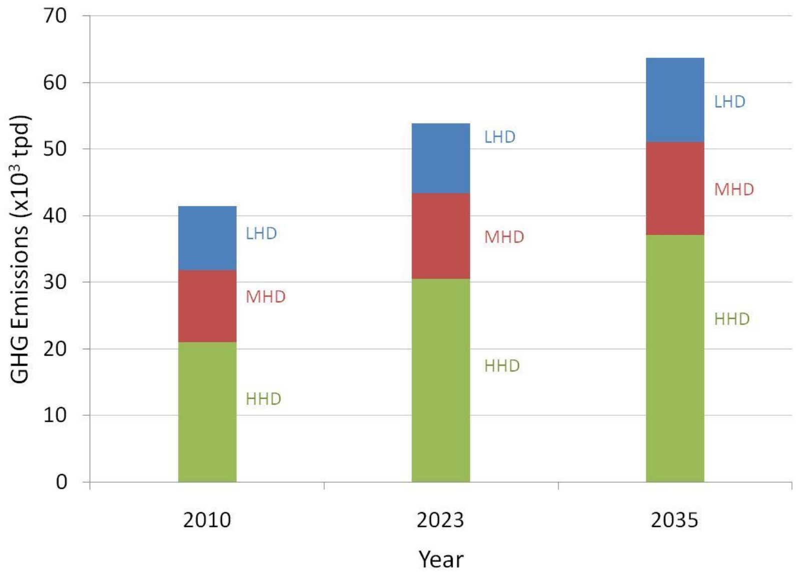


Exhibit 2-12: Heavy-Duty Vehicle GHG Emissions, South Coast Air Basin



Results – SCAG Region Inventory

To estimate emissions in the SCAG area, we ran EMFAC2007 in the county mode for each of the six SCAG counties. Truck populations were adjusted as described above. First, recession adjustment factors were applied to model years 2007 through 2023 for both MHD and HHD truck populations. Then the pre-2010 truck population was redistributed to model year 2010+ truck populations.

See Appendix A for the MHD and HHD truck populations calculated for each county in the SCAG region. Appendix A also contains tables with emissions results by county for 2023 and 2035.

Exhibits 2-13, 2-14, and 2-15 show truck emissions for the entire SCAG area in 2010, 2023, and 2035.

Exhibit 2-13: Heavy-Duty Vehicle Emissions, SCAG Region, 2010

Vehicle Class	Fuel	Pop	VMT (10^6)	Tons per day							
				NOx	$PM_{2.5}$			PM_{10}			GHGs
					Exh	T&B	Total	Exh	T&B	Total	
LHD1	Gasoline	156,986	7.363	17.595	0.072	0.067	0.140	0.079	0.198	0.277	7,618
	Diesel	33,928	1.749	9.945	0.059	0.016	0.075	0.061	0.047	0.110	1,274
	All	190,954	9.113	27.498	0.131	0.083	0.214	0.140	0.244	0.386	8,893
LHD2	Gasoline	33,863	1.533	3.553	0.014	0.015	0.030	0.016	0.040	0.058	1,584
	Diesel	26,339	1.187	8.446	0.052	0.010	0.062	0.059	0.033	0.089	881
	All	60,197	2.720	11.979	0.065	0.024	0.092	0.074	0.073	0.147	2,467
MHD	Gasoline	22,550	1.046	5.515	0.014	0.008	0.022	0.015	0.029	0.044	1,167
	Diesel	78,881	5.076	52.479	1.201	0.046	1.249	1.307	0.135	1.445	11,117
	All	101,432	6.122	58.057	1.214	0.054	1.271	1.321	0.164	1.489	12,284
HHD	Gasoline	5,389	0.596	8.527	0.009	0.005	0.020	0.009	0.024	0.039	741
	Diesel	78,490	13.706	251.440	11.007	0.318	11.343	11.971	0.971	12.960	38,175
	All	84,969	14.313	260.014	11.013	0.326	11.361	11.977	0.996	12.998	38,930
All HD	Gasoline	218,272	10.410	34.241	0.109	0.095	0.208	0.118	0.286	0.409	10,948
	Diesel	217,547	22.383	329.693	11.529	0.398	12.008	12.539	1.210	13.935	52,612
	All	435,750	33.297	352.589	11.481	0.503	12.003	12.493	1.524	14.042	64,319

T&B=Tire and Brake emissions

Exhibit 2-14: Heavy-Duty Vehicle Emissions, SCAG Region, 2023

Vehicle Class	Fuel Type	Pop	VMT (10^6)	Tons per day							
				NOx	PM2.5			PM10			GHGs
					Exh	T&B	Total	Exh	T&B	Total	
LHD1	Gasoline	201,840	8.867	13.796	0.101	0.081	0.183	0.110	0.240	0.349	8,329
	Diesel	48,024	2.109	5.390	0.052	0.019	0.071	0.054	0.057	0.112	1,381
	All	249,864	10.976	19.186	0.153	0.100	0.254	0.164	0.297	0.461	9,710
LHD2	Gasoline	43,166	1.889	2.726	0.020	0.017	0.038	0.022	0.049	0.073	1,772
	Diesel	32,837	1.409	3.769	0.034	0.012	0.047	0.039	0.038	0.076	926
	All	76,003	3.298	6.495	0.054	0.029	0.085	0.061	0.087	0.149	2,698
MHD	Gasoline	26,980	1.318	2.368	0.018	0.011	0.029	0.019	0.036	0.055	1,240
	Diesel	94,426	7.007	8.467	0.637	0.063	0.702	0.693	0.188	0.883	13,267
	All	121,406	8.325	10.835	0.655	0.074	0.731	0.712	0.224	0.938	14,507
HHD	Gasoline	2,866	0.279	2.599	0.004	0.003	0.010	0.004	0.012	0.017	290
	Diesel	97,441	23.647	78.838	2.511	0.551	3.062	2.732	1.674	4.405	56,310
	All	100,307	23.926	81.437	2.515	0.554	3.072	2.736	1.686	4.422	56,600
All HD	Gasoline	274,852	12.353	21.489	0.143	0.112	0.260	0.155	0.337	0.494	11,630
	Diesel	272,728	34.172	96.464	3.234	0.645	3.882	3.518	1.957	5.476	71,885
	All	547,580	46.525	117.953	3.377	0.757	4.142	3.673	2.294	5.970	83,515

T&B=Tire and Brake emissions

Exhibit 2-15: Heavy-Duty Vehicle Emissions, SCAG Region, 2035

Vehicle Class	Fuel Type	Pop	VMT (10^6)	Tons per day							GHGs
				NOx	PM2.5			PM10			
					Exh	T&B	Total	Exh	T&B	Total	
LHD1	Gasoline	239,678	10.467	12.989	0.121	0.096	0.218	0.131	0.283	0.415	10,066
	Diesel	56,018	2.427	3.569	0.050	0.021	0.071	0.053	0.065	0.118	1,589
	All	295,696	12.894	16.558	0.171	0.117	0.289	0.184	0.348	0.533	11,655
LHD2	Gasoline	51,760	2.253	2.506	0.024	0.021	0.046	0.026	0.063	0.088	2,169
	Diesel	38,180	1.643	2.255	0.031	0.016	0.045	0.034	0.044	0.077	1,076
	All	89,940	3.896	4.761	0.055	0.037	0.091	0.060	0.107	0.165	3,245
MHD	Gasoline	32,230	1.560	1.616	0.022	0.013	0.035	0.023	0.042	0.065	1,495
	Diesel	122,888	7.496	10.415	0.858	0.068	0.928	0.933	0.203	1.135	14,202
	All	155,118	9.056	12.031	0.880	0.081	0.963	0.956	0.245	1.200	15,697
HHD	Gasoline	2,690	0.335	2.297	0.006	0.004	0.012	0.006	0.015	0.020	339
	Diesel	149,204	30.151	112.016	3.492	0.700	4.193	3.798	2.134	5.931	71,978
	All	151,894	30.486	114.313	3.498	0.704	4.205	3.804	2.149	5.951	72,317
All HD	Gasoline	326,358	14.615	19.408	0.173	0.134	0.311	0.186	0.403	0.588	14,069
	Diesel	366,290	41.717	128.255	4.431	0.805	5.237	4.818	2.446	7.261	88,846
	All	692,648	56.332	147.663	4.604	0.939	5.548	5.004	2.849	7.849	102,915

T&B=Tire and Brake emissions

3. Truck Technological Strategies

To achieve significant emission reductions from heavy-duty trucks beyond the baseline presented in Section 2 will require deployment of one or more advanced technologies. In the following subsections, we review four advanced truck technology strategies for goods movement:

- advanced natural gas engines
- hybrid technologies
- plug-in hybrid technologies
- battery electric technologies

For each technology, this report presents:

- A review of the current state of technology, including a discussion of: a) the most likely markets or applications that the technology will serve; b) the estimated costs of the technology; and c) the environmental benefits
- A review of the barriers to advancement
- An assessment for the potential for advancement in light of the barriers identified

Heavy-duty trucks have a wide range of operational characteristics (e.g., duty cycle or miles traveled). To assess the potential suitability, benefits, and costs of advanced truck technologies, we selected three proxy vehicles to represent goods movement in the heavy-duty sector – a Class 3 truck (2 axles), a Class 6 truck (3 axles) and a Class 8b combination truck (5 axles). Exhibit 3-1 summarizes these three vehicle types.[6]

Exhibit 3-1. Overview of Selected HD Truck Characteristics for Goods Movement Sector

Truck Class	Applications	Engine		Avg Fuel Economy (mpg)
		horsepower	torque	
Class 3 10,001-14,000 lbs single unit, 2 axle	Step Van Parcel Delivery	varies	varies	10.5
Class 6 19,501-26,000 lbs single unit, 3 axle	City Delivery Large Walk-in	200-350 hp	500-1000 lb-ft	7.0
Class 8b >60,000 lbs combination truck	Drayage Regional Haul	250-600 hp	1300-1850 lb-ft	5.7

3.1. Advanced Natural Gas Technologies

Current Status and Market Opportunities

Heavy-duty natural gas vehicles (NGVs) are used in many applications; they were originally deployed in niche applications involving centralized fueling locations such as refuse haulers and transit buses. Today, natural gas engines have the performance characteristics to be applied in a number of goods movement applications. The primary operational characteristic that limits the potential for HD NGVs in the goods movement sector is vehicle range. Although the vehicles have sufficient range for regional haul

[6] Average fuel economy from 2002 Vehicle Inventory and Use Survey, U.S. Bureau of Census.

applications, the onboard storage capacity for compressed natural gas (CNG), and to a lesser extent liquefied natural gas (LNG), limits the potential of the technology in long haul applications. The potential for HD NGVs in the regional haul market is highlighted by the 700 NG trucks deployed at the San Pedro Bay Ports since 2009 as part of the Clean Trucks Program. Furthermore, as part of ARRA funding, the Clean Cities program awarded about $300 million of grants with an estimated $150 million going towards 18 projects involving CNG or LNG, including the deployment of nearly 1600 medium- and heavy-duty NGVs (most will be heavy-duty) and 82 new natural gas fueling stations and 38 station upgrades. Several of the selected projects will benefit the SCAG region, including:

- SCAQMD, in coordination with UPS, was awarded nearly $6 million for the Ontario-Las Vegas LNG Corridor Expansion Project to deploy 48 LNG trucks in UPS's fleet and build an LNG station off of I-15 in Las Vegas.
- SCAQMD also received about $9.4 million to replace 180 drayage trucks at the ports; the funding also includes an education and outreach component to be developed by SCAG.
- Finally, the San Bernardino Associated Government, in coordination with JB Hunt, was awarded nearly $10 million to deploy 262 LNG trucks and 2 LNG fueling stations in San Bernardino and South Los Angeles.

The federal government has dedicated little funding for research and development for natural gas in the transportation sector for a number of reasons, including the availability of significant purchase incentives – for vehicles, infrastructure, and fuel. Recently, however, there was a small but symbolic congressionally directed investment made as part of the DOE/EERE Vehicle Technologies Program. This $5 million investment was matched by funds from the PIER Program at the California Energy Commission ($4 million) and the South Coast Air Quality Management District ($4 million), with a total of nearly $13 million of funding available for research and development related to natural gas engines. The following is a brief description of the 4 projects selected to participate in the program:

- Cummins Westport Inc. (CWI) and Autocar will develop the 11.9 L Cummins engine using spark ignited CNG. CWI and Autocar have proposed to integrate the engine into a refuse application for demonstration.
- Southwest Research Institute (SwRI) and Autocar are working on a similar project; however, they are using a Doosan Infracore engine.
- Emissions Solutions will work on a repower kit for the 13 L Navistar engine using spark ignited CNG with the goal of deploying a wide range of engine-vehicle combinations.
- ISE Corporation received funds to develop a spark ignited CNG 6.8 L Ford engine with the hope of integrating a series hybrid configuration for demonstration.

The California Energy Commission has also funded the Gas Technology Institute to help bring the Cummins Westport ISX 11.9L G to market. The project is focused on late stage development, demonstration, and product launch. The demonstration is set to run through 2013 with product launch shortly thereafter; Cummins Westport anticipates producing 4,000-6,000 units per year in the first 5 years of production.

In the early 2000s, Federal and State government agencies showed interest in using hydrogen enriched natural gas in natural gas engines to reduce NOx and as a potential bridge to using hydrogen in fuel cell applications. For hydrogen/natural gas blends, generally about 20% hydrogen and 80% natural gas (by volume) are used. Natural gas engines can operate with these blends without major modifications; up to 50% NOx emissions reductions have been reported in some cases. Southern California has been a leader in supporting the deployment of hydrogen fuel cell vehicles (FCVs); however, the goods movement sector has not been a prime target of hydrogen or hydrogen/natural gas blends. There were multiple demonstration projects for hydrogen/natural gas blends, particularly in the transit sector around 2005; however, interest in this area has not been sustained.

Environmental Benefits

Natural gas vehicles can reduce both NOx and particulate matter emissions from heavy-duty vehicles. Potential NOx emission reductions are in range of 20-30%, depending on the application. The ISL GX (14.9 L displacement) from Westport, for instance, is certified at 0.13 g/bhp-hr for NOx, while comparable 14.9L diesel engines from Cummins are certified at 00.18 g/bhp-hr of NOx.[7] For the 8.9L engine, Cummins certifies the natural gas version at 0.1 g/bhp-hr NOx and the diesel version at 0.22 g/bhr-hr NOx.[8] The effect on PM emissions is less certain. While the Westport and Cummins engines mentioned above have shown significant PM benefits, natural gas trucks operated at the Port of Los Angeles are showing greatly increased ammonia emissions relative to diesel trucks.[9] Ammonia can produce secondary particulates that could offset the particulate matter benefits of natural gas. We assume PM benefits in the range of 10% – 30% for compared to conventional diesel. For gasoline trucks, natural gas offers no significant PM benefit.

The GHG benefits of using natural gas in a heavy-duty application were calculated on a lifecycle basis using carbon intensities (in grams of carbon dioxide equivalents per unit of energy, g CO2eq/MJ) and energy economy ratios (EERs) reported by ARB in the Low Carbon Fuel Standard.[10] The lower limit of the GHG reduction is calculated using the pathway described as North American NG delivered via pipeline and compressed in CA. The upper limit of the GHG reductions is calculated assuming a blend of the aforementioned North American NG (at 75%) and landfill gas that has been upgraded to pipeline quality (25%). The calculations performed assumed a 10% reduction in fuel economy attributable to natural gas trucks. Traditionally, spark-ignited and compression ignition natural gas engines have had a fuel economy penalty, which depends on a number of factors such as load and duty cycle; the fuel economy penalty for spark-ignited engines in goods movement applications is likely around 10% whereas for compression ignition it is less than 5%.

A transition to hydrogen/natural gas blends for use in heavy-duty vehicles would produce an additional 5-15% in NOx emission reductions, depending on the application and the ratio of hydrogen to natural gas used. Exhibit 3-2 summarizes the per truck emission benefits of natural gas HDVs used for this report.

Exhibit 3-2. Emissions Benefits of Advanced Natural Gas HDVs (per truck)

Advanced NGVs	Class 3			Class 6			Class 8b		
	NOx	PM2.5	GHGs	NOx	PM2.5	GHGs	NOx	PM2.5	GHGs
Diesel	20-30%	10-30%	20-37%	25-35%	10-30%	20-37%	35-50%	10-30%	20-37%
Gasoline	20-30%	0%	21-38%	25-35%	0%	21-38%	N/A	N/A	21-38%

[7] ARB Executive Orders: A-343-006, Westport Fuel Systems; A-021-0528-1 for Cummins Inc.; July 2010.

[8] ARB Executive Orders: A-021-518, Cummins Inc., A-021-0524, Cummins Inc.; December 2009.

[9] Remote measurements of on-road emissions from heavy-duty diesel vehicles in California; Year 3, 2010, B.G. Schuchmann, G.A. Bishop and D.H. Stedman, Final Report prepared for NREL, November 2010. Available at http://www.feat.biochem.du.edu/assets/databases/Cal/CA_HDDV_final_report_2010_NREL_version.pdf

[10] Final Regulation Order, Subchapter 10, Article 4, Subarticle 7. Low Carbon Fuel Standard.

Costs

The most significant portion of the incremental cost of natural gas vehicles is the fuel storage system, consisting of cylindrical tanks to store CNG at high pressure. These costs are not expected to change significantly over time, and natural gas cylinders are already manufactured in high volumes for other applications. The estimated incremental costs for heavy-duty NGVs, by class, are shown in Exhibit 3-3.[11] A small reduction of incremental costs of NGVs over time is attributed to increased manufacturing volumes of engines; the base incremental cost remains, regardless of production volumes, because we do not estimate significant reductions in the cost of fuel and fuel storage systems (i.e., cylinders). In each case, the incremental cost in 2035 assumes at least parity in the manufacturing volumes of diesel and natural engines, meaning that the only difference in price is attributable to fuel storage systems.

Exhibit 3-3. Estimated Commercial Availability and Incremental Cost of Advanced Natural Gas HDVs

Advanced Natural Gas Vehicles	Commercial Availability	Incremental Costs		
		today	2023	2035
Class 3 Step Van / Box Van	available today	$15-20k	$13-18k	$10-14k
Class 6 Box Truck	available today	$25-35k	$23-32k	$20-28k
Class 8b Regional Haul	available today 13-15 L engines available 2013-2015	$35-45k	$32-40k	$28-36k

We must also consider the infrastructure costs for natural gas vehicles. There is a wide range of costs associated with retail fueling stations. For instance, in an analysis for the Federal Transit Administration, West Virginia University reports CNG stations ranging from $320,000 to $7,400,000.[12] These ranges are an indication of the unique conditions that contribute to the costs of retail fueling stations. The range of estimates for CNG fueling stations are listed in Exhibit 3-4.[13]

[11] Energy Information Administration, *Annual Energy Outlook 2010, Natural gas as a fuel for heavy trucks: Issues and incentives*, Report #DOE/EIA-0383

[12] USDOT/FTA, *Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation*, FTA-WV-26-7004.2007.1, July 2007

[13] ICF report to California Energy Commission, Fuel Infrastructure and Distribution Development for Natural Gas, Draft Report, November 2010

Exhibit 3-4. Estimates of CNG Fueling Station Costs, by Type and Application

Type	Applications	Compression (CNG) Storage (LNG)	Cost
CNG	small, medium, and large fleets ◆ Local buses ◆ Refuse haulers	2,300 scfm @ 3,600 psi	$0.5–5.5 million
CNG, landfill	medium fleet ◆ regional delivery/pickup vehicles ◆ construction equipment ◆ local taxi fleet and private vehicles	900 scfm @ 3,600 psi inc. slow-fill capability	$2–3 million
CNG, various	small and medium fleets regional use vehicles	100 scfm @ 3,600 psi	$0.3–0.35 million
LNG-to-CNG	medium fleet regional transit vehicles	15,000 gallons/tank AST or UST	$2–5 million

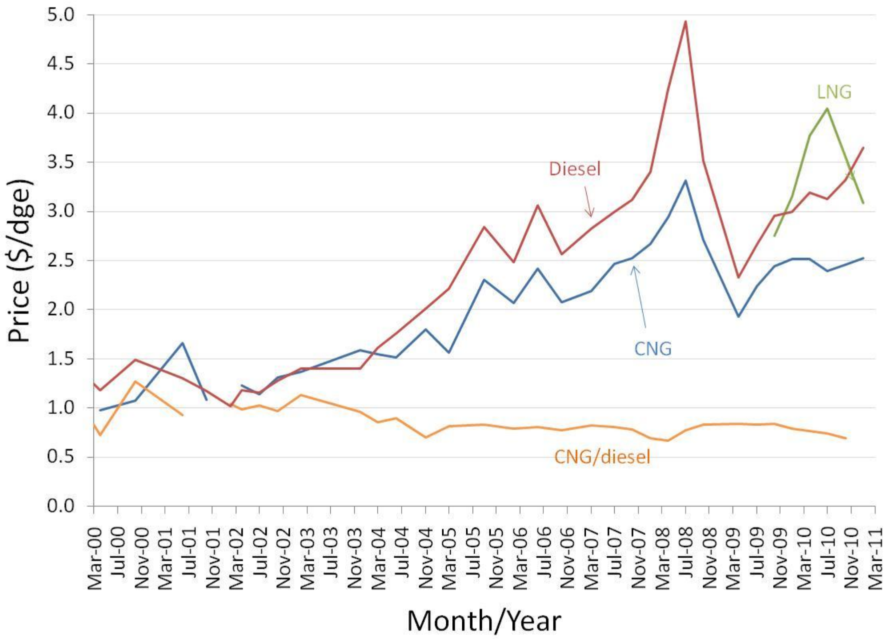
Barriers to Advancement

The value proposition of HD NGVs is dependent on fuel pricing and fuel availability. Operators will need to recover the incremental capital costs of vehicles in an acceptable time frame. In the goods movement sector, operators generally expect a payback in the range of 2-5 years.

There are several factors that affect the price of natural gas at the pump. Apart from the price of natural gas as a commodity, the most important factor in determining fuel price at the pump is the cost of capital recovery, which is a function of demand or throughput capacity. For instance, as part of *AEO2010*, the Department of Energy analyzed the impacts of increasing the throughput capacity of a CNG station from 1,250 to 5,000 gallons (of diesel equivalents) per day, and report that at the higher volume, the capital recovery costs are lowered by more than $1.00/dge. At this point, there is not sufficient demand to increase throughput capacity and lower the price of natural gas at the pump.

Exhibit 3-5 highlights the close relationship between CNG and diesel prices. On an energy equivalent basis, natural gas is selling for approximately 30 percent less on the West Coast than diesel fuel today, which is notably less than the previous 6 year average of 20 percent (the standard deviation over the 6-year period is 6%). In other words, the recent increase in oil prices and decreasing or unchanged price in natural gas has shown up at the pump, according to the Alternative Fuel Price report. Oil prices are increasing at a faster rate than natural gas prices (in the US), due in large part to downward pressure on the price of natural gas due to recent increases in estimated domestic supply.

Exhibit 3-5. Natural gas and diesel prices on the West Coast ($2008)



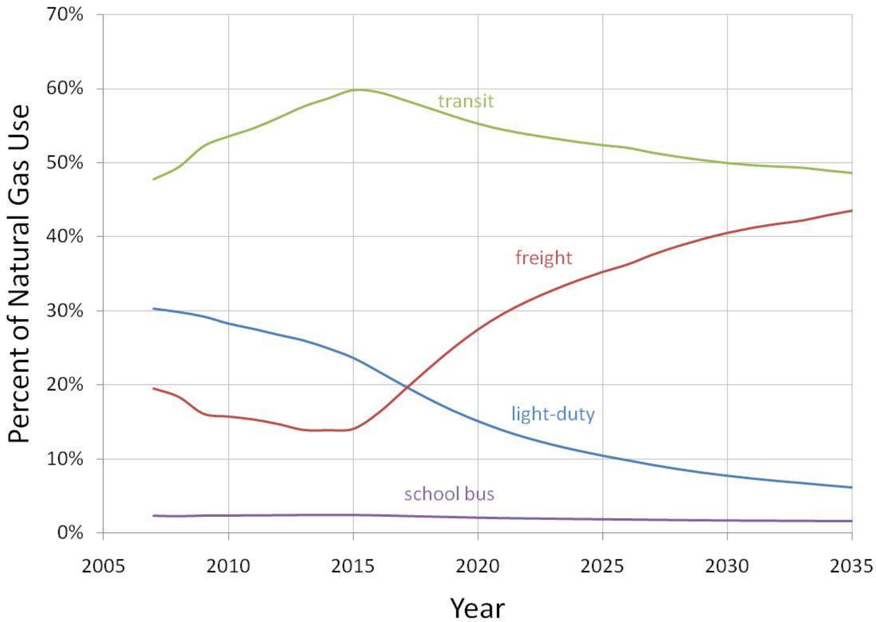
Source: Data reported in Clean Cities Alternative Fuels Price Report, March 2000-July 2010, http://www.afdc.energy.gov/afdc/price_report.html

There has been a considerable amount of research regarding the relationship between wholesale natural gas prices (i.e., not CNG at the pump) and crude oil prices. Many analysts use ratios e.g., 6-to-1 (based on energy content of a barrel of oil) or 10-to-1 (observational) to relate crude oil prices and natural gas prices. Brown and Yücel found a more complex and subtle relationship between crude oil prices and natural gas prices, explained by weather, seasonality, storage, and production disruption (e.g., hurricanes).[14] They found that an error-correction model accurately predicted natural gas prices by starting with crude oil prices and correcting for these factors, concluding that the short-term dynamics are complex, but stable in the long run. Today, many industry analysts who believe that natural gas prices will de-couple from oil prices, due in large part to the drastic increase in reported natural gas reserves. Similarly, the *AEO2010* expects the gap between diesel and natural gas prices to increase over time. On the other hand, these types of variations have been observed previously and many industry observers think it is likely that we are in a period of short-term dynamics, rather than establishing a new trend.

Most observers agree that natural gas is a good fit for the medium- and heavy-duty truck market. For example, in the Reference Case of the *AEO2010*, the Department of Energy assumes the percentage of vehicles consuming natural gas changes drastically over time, as shown in Exhibit 3-6. The *AEO2010* essentially projects a complete turnover and retirement of the light-duty NGV fleet. The increase in fuel consumption is driven by a doubling in the percent of total natural gas consumed by freight trucks. This is especially relevant in the goods movement sector, however, this will require significant investments in the refueling infrastructure in California.

[14] Brown, S. and Yücel, MK. *What Drives Natural Gas Prices?* Federal Reserve Bank of Dallas, Research Department Working Paper 0703, February 2007.

Exhibit 3-6. Percent of NG Use, by Sector from *AEO2010* Reference Case



On the supply side, recent concern regarding hydraulic fracturing may become a barrier. The recent increase in domestic reserves is largely attributable to advances in hydraulic fracturing, which involves the injection of fluids – generally water and chemical additives – at high pressure. As the pressure exceeds the rock strength, the fluids open or enlarge fractures. Propping agents are used to maintain the fractures after the pumping pressure is released. The fluids then rise to the surface; however, there is concern that the fluids contain chemicals that threaten the safety of drinking water. Similarly, elevated levels of dissolved methane in drinking water have been measured near sites using hydraulic fracturing. Due in part to pressure from communities and environmental groups, the EPA recently issued a voluntary information request to firms that specialize in hydraulic fracturing, seeking information on the chemical composition of the fluids used in the process. Although we do not perceive supply as a barrier to expansion, recent issues regarding the health and safety risks associated with hydraulic fracturing should give pause to an overly aggressive forecast.

Potential for Advancement

Natural gas vehicles have significant potential for advancement across all heavy-duty truck sectors; however, this potential is contingent upon several factors.

- To realize the potential cost savings from natural gas vehicles – a significant benefit from an owner-operator standpoint – there must be a sustained price differential between natural gas and diesel.
- There are government incentives in place for both vehicle purchase and infrastructure development. To improve the business case for natural gas stations, throughput at stations must increase, which will require a steady increase in the number of vehicles.
- There are many natural gas engines available that are certified to meet the 2010 standards, with new offerings being developed by manufacturers such as Cummins Westport Inc., Doosan Infracore, and Volvo Technology. As noted above, natural gas engines have low tailpipe PM emissions but have

shown much higher ammonia emissions, which can lead to particulate formation.[15] For NOx, these engines certify between 0.13 and 0.20 g/bhp-hr using federal test procedure. Although these emissions factors are low enough to certify for 2010 standards, the focus here is on potential to reduce emissions further. On the engine development side, improvements are largely dependent on how well engine manufacturers can control the air-to-fuel ratio – the key determinant in NOx emissions. Engine manufacturers are already employing selective catalytic reduction technology (e.g., Doosan Infracore) or a three way catalyst (e.g., Cummins Westport) to reduce NOx emissions.

- Engine manufacturers are starting to fill the need for offerings in goods movement applications with higher horsepower requirements (i.e., 400-600 hp) and larger displacement (i.e., 12-16 L). However, these efforts will require more testing and certification. These products will likely not launch until 2013 at the earliest and will not see significant market penetration until 2015 at the earliest, depending of factors such as incremental pricing, operational costs, and fueling infrastructure availability.
- Recent increases in the supply of domestic natural gas is a major contributor to the significant potential for advancement; however, should environmental concerns and costs related to hydraulic fracturing eventually outweigh the benefits, then the expansion of natural gas vehicles in the heavy-duty sector will be limited.

Regarding hydrogen/natural gas blends, ICF does not predict a significant penetration in the heavy-duty sector unless there is a convincing case that truck manufacturers and operators are moving towards heavy-duty fuel cell vehicles. This would provide the bridge for hydrogen/natural gas blends that policy makers envision for more significant GHG emission and criteria pollutant emission reductions. At the current time, however, demonstrations and activities related to hydrogen/natural gas blends have decreased significantly and the potential for dedicated fuel cell vehicles (i.e., not used in a hybridized power train) in the heavy-duty sector is low.

3.2. Hybrid Technologies

Current Status and Market Opportunities

The hybrid truck sector is a nascent part of the truck manufacturing industry but has evolved quickly. In this category we consider electric hybrids and hydraulic hybrids in various configurations. Plug-in hybrid vehicles, which can draw electricity from the grid to charge a battery, are considered separately in the next section.

We focus on two types of hybrid powertrains: an engine and either an a) electric motor/generator combination or b) mechanical/hydraulic components. Hybridized powertrains offer significant advantages in the goods movement sector, including reduced emissions, the potential for reduced life cycle costs via maintenance and fuel savings, and improved driving characteristics. The vehicle architecture for hybrids varies considerably, but can be generally characterized into three categories: series, parallel, and power split:

- In the series hybrid architecture, an electric generator is coupled to an engine and supplies electricity to propel the vehicle. The engine is decoupled from the drivetrain and acts as a power source for the generator.

[15] High ammonia emissions were found with NG engines that were stoichiometric and used three-way catalysts (TWC). This is likely due to the large rich excursions these vehicles have when accelerating. High unburned natural gas when passed over a TWC forms ammonia. MY 2009 lean burn engines did not show this dramatic increase. NG engines may need to use lean burn technology with SCR to control NOx emissions in order to mitigate high ammonia emissions.

- In the parallel hybrid configuration, both an internal combustion engine and the electric motor are connected to the wheels. In this configuration, the electric motor generally assists the engine during startup and acceleration. A parallel configuration is generally considered a more likely near-term option for medium-duty and heavy-duty vehicles, and may be considered a mild hybridization, depending on the application.
- The power split hybrid configuration is a combination of the series and parallel hybrids to increase efficiency. This is achieved by distributing engine power to the drive shaft and the generator. The former goes directly to the wheels and the latter is stored as electric energy in the battery.

Hybrid Electric Trucks

Hybrid electric technology increases system efficiency by introducing an electric motor and generator, an energy storage device (e.g., a battery), and power electronics. The electric motor and generator absorb energy via regenerative braking and store that energy in, for instance, a battery to offset acceleration and power demands of the vehicle. This system is optimized for vehicles depending on the demands of the likely duty cycle.

By 2008, every major truck manufacturer had at least one hybrid offering. CalSTART reports that at least 3,500 hybrid trucks were on the road nationwide or had been ordered by the end of 2010. The market for hybrid trucks (and buses) has been accelerated significantly with the implementation of the Hybrid Truck and Bus Voucher Incentive Project (HVIP) in California, administered by ARB. The HVIP helped deploy more than 650 vehicles in the first year of the program (nearly 20% of the estimated hybrid truck population) with approximately $19 million in awards. The incentives provided by the HVIP are considered essential by the industry and have been a significant driver for fleets.

Daimler Trucks led a project that was funded by the California Energy Commission to develop an advanced hybrid electric truck (in the Class 6-8 range) in a series hybrid configuration fueled by natural gas. Daimler teamed with engine manufacturer Cummins Westport and BAE Systems, a hybrid powertrain developer. The initial proposal included a demonstration phase running through the end of 2012, with a target of producing 1,500 units per year by 2014. Furthermore, the initial proposal included a task that would have had Daimler develop a white paper outlining the steps necessary to transition to a zero (tailpipe) emissions solution using an overhead catenary system.

Hybrid electric vehicles are considered viable for all goods movement applications.

Hydraulic Hybrid Trucks

Hydraulic hybrid technology increases system efficiency using hydraulic accumulators to convert and store energy from braking as pressurized hydraulic fluid; the efficiency gains are realized through regenerative braking, optimized engine control and engine shut-off during deceleration and idling. The technology is ideal for power driven applications with low energy requirements. Hydraulic hybrids are still in the demonstration/prototype phase.

For instance, the California Energy Commission is funding a project led by Parker Hannifin, Daimler Trucks, Cummins Inc, and FEV Group to develop a hydraulic hybrid beverage delivery vehicle (the proposal initially listed Coca-Cola Enterprises as the lead applicant; that has since been amended). The project team hopes to demonstrate a vehicle with a series hybrid configuration in a Class 8 truck with applicability to Class 6 and 7. The appeal of the hydraulic hybrid system is the simplicity of the primarily mechanical application as opposed to the electrical components of a hybrid electric system. Furthermore, proponents of the hydraulic hybrid configuration claim fuel economy benefits ranging from 25-30% better than hybrid electric technology.

UPS received ARRA funding via the Clean Cities solicitation to deploy hydraulic hybrid vehicles in the Metropolitan Area and elsewhere. The vehicles will be distributed by Freightliner (a Daimler subsidiary) and built using Parker Hannifin's hydraulic hybrid system.

Hydraulic hybrids are best suited to stop-and-start applications such as refuse haulers or delivery trucks. Although they can be designed for other goods movement applications, the magnitude of benefits in these applications e.g., regional haul, may be lower.

Emissions Benefits

The emissions benefits of hybrids are highly dependent on the duty cycle of the vehicle, particularly the amount of time spent at lower speeds and higher torque. The degree of the hybridization is also a factor in the estimation of emissions benefits. For instance, the NRC report estimates that full electrification of accessory loads, integration of hybrid system with the emissions control, and engine downsizing in some applications may yield an additional 5-10% fuel consumption benefit.[16] In the configurations more common today – a parallel configuration with a battery between 2-3 kWh and a motor ranging from 40-120 kW – emission reduction benefits should be on the same order as fuel consumption benefits; they could be slightly higher when duty cycles include lower speeds, significant idle time, and extended time in stop-and-go traffic.

Note, however, that fuel savings alone will not automatically translate into NOx and PM reductions. Manufacturers design emission control systems to meet the federal and state emissions standards. If a vehicle model uses less fuel, the manufacturer could install a less effective (and less expensive) emission control system and still meet the standards. Thus, ensuring that the NOx and PM emissions benefits of hybrid technology are realized might require additional performance standards or incentives.

There is limited field and laboratory testing available for hybrid electric and hydraulic hybrid trucks. We reviewed the available information to develop estimates for emissions reductions. Eaton reports a 30% fuel economy improvement in city delivery applications, with similar criteria pollutant reductions. Similarly, Eaton reports 20-30% and 50-70+% improved fuel economy with corresponding reductions in criteria emissions in a parallel and series hydraulic hybrid configuration, respectively.[17] CALSTART reports 30-60% reductions in hybrid electric utility truck (Class 6/7) in a parallel configuration, with a small battery (1.1 kWh).[18] Although the trucks/applications presented here differ from a utility truck, particularly in duty cycle and power take-off, this is a useful data point, particularly for the Class 3 truck in an urban delivery application making many stops.

To estimate emissions benefits, we analyzed emission by speed using EMFAC. We assumed that all idling and travel less than 10 mph would be battery powered and therefore produce zero emissions. For travel at higher speeds, internal combustion engine operation would drive the vehicle, thus NOx and PM2.5 exhaust emissions would be unchanged. Because of regenerative braking in hybrid vehicles, we assumed PM2.5 emissions from brake wear would be half that of a conventional vehicle. GHG emissions

[16] National Research Council, *Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles*, 2010.

[17] Cornils, H. *Hybrid Solutions for MD Commercial Vehicles*, ERC Symposium, University of Wisconsin, Madison, June 2009.

[18] Van Amburg, B. *Hybrid Medium and Heavy-Duty Trucks: On the Cusp of Production*, CALSTART, October 2007.

reductions for hybrid electric trucks are shown here based on fuel consumption benefits reported by the National Academies recent report on fuel economy in medium- and heavy-duty vehicles.[19]

Our estimated per truck emission reductions for NOx, PM2.5, and GHGs are shown in Exhibit 3-7.

Exhibit 3-7. Emissions Benefits of Hybrid HDVs (per truck)

Hybrid Vehicles	Class 3			Class 6			Class 8b		
	NOx	PM2.5	GHGs	NOx	PM2.5	GHGs	NOx	PM2.5	GHGs
Diesel	42-62%	25-45%	20-35%	36-56%	9-29%	20-35%	31-41%	4-24%	5-20%
Gasoline	11-21%	21-31%	20-35%	8-18%	21-31%	20-35%	N/A	N/A	N/A

Costs

We developed estimated incremental costs for hybrid electric vehicles based on the additional costs of hardware, labor, fixed costs to the manufacturer, and the manufacturer's markup. The hardware costs include the motor/generator, the battery pack, power electronics, modified clutch assembly, and the electrification of accessories. The fixed costs are those that are considered constant, regardless of the number of units that are ultimately manufactured. Fixed costs include research and development (R&D), tooling costs, and an estimated 5-year recovery on investment. In other words, these are costs that manufacturers will bear when they invest in new and advanced technologies, and will factor these costs into their pricing schemes for return on their investment. The recovery on investment in R&D and tooling is a common business practice that enables for-profit companies to recoup investments while continuing to reinvest in R&D and technological advancements. Based on ICF estimates, the incremental costs of hybrid electric trucks are shown in Exhibit 3-8.

Exhibit 3-8. Estimated Commercial Availability and Incremental Costs of Hybrid HDVs

Hybrid Vehicles	Commercial Availability	Incremental Costs		
		today	2023	2035
Class 3 Step Van / Box Van	hybrid electrics available today hydraulic hybrids in 2015	$10-15k	$8-12k	$6-10k
Class 6 Box Truck	hybrid electrics available today hydraulic hybrids in 2015	$35-40k	$20-30k	$15-20k
Class 8b Regional Haul	limited availability today more offerings over 2-3 yrs; hybrid electric and hydraulic hybrid	$55-60k	$40-50k	$25-35k

While the costs of hydraulic hybrids were not estimated in this report, we assume that the range of cost for hybrid electric and hydraulic hybrid trucks is similar. As part of a demonstration project, the EPA estimated a payback period of less than 3 years for hydraulic hybrids in an urban delivery application when manufactured at high volumes. The costs savings are realized via fuel savings (estimated 60% improvement in fuel economy) and reduced maintenance costs. While the value proposition for each technology will vary depending on the duty cycle, the 3-year payback period estimated by EPA for

[19] *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles,* National Academy of Science, 2010.

hydraulic hybrids is similar to 5-year estimate for the estimate for hybrid electric vehicles currently on the market. As such, the estimated incremental costs of hydraulic hybrid systems are likely to be similar to hybrid electric vehicles if both are manufactured at high volumes.

There are no additional fueling infrastructure cost requirements for hybrid vehicles unless they are using an alternative fuel e.g., natural gas. For cost estimates of natural gas fueling infrastructure, see previous section.

Barriers to Advancement

The incremental cost of hybrid trucks is the main barrier to advancement. As discussed previously, aggressive government incentives have been introduced to overcome this barrier. The significance of the vehicle price barrier is dependent on the price of fuel. As the price of diesel declined after its peak in 2008, interest in hybrid trucks waned. The value proposition to owner-operators of hybrid trucks (i.e., operational savings via improved fuel economy) is tied to the cost of fuel. Similarly, the economic recession also shifted interest from purchasing new vehicles to extending the life of the existing fleet.

Despite many offerings in the LHD and MHD sectors, there are limited vehicle offerings in the Class 8 sector at this time; however, this is likely to change in the near future.

The reluctance of the trucking industry to adopt a new technology is also a barrier to advancement. However, the regulations and concerns regarding air quality are much more significant in Southern California than other areas, and the trucking industry here is therefore more accepting of new technologies.

Potential for Advancement

Hybrid trucks are set to make significant gains over the next several years, as a result of the following:

- There are many federal and state incentives in place to help reduce the upfront costs. The high level of interest from large fleets, e.g., Pepsi and Coca-Cola, in the incentive programs demonstrates the significant potential of hybrid technology. If government incentives and the interest of large fleets can continue to spur the early market for hybrid trucks, then this will enable manufacturers to benefit from large production volumes.
- The new fuel economy standards proposed by EPA and NHTSA will help the heavy-duty market transition from mild to full hybridization. The trend towards more fuel efficient vehicles in the LHD, MHD, and HHD sectors will also decrease the incremental cost of hybrid configurations.
- The recent increase in diesel prices at the pump are more likely to be sustained than in 2008, potentially inducing owner-operators to purchase hybrid vehicles.
- The small but consistent gains in the economy over the last 18 months will likely spur greater interest and increase fleet turnover, reaching levels similar to those previous to the most recent recession.
- Hybrid vehicles are gaining significant momentum in the heavy-duty sector and are set to overcome some of the key inertial barriers of some owner-operators. As volumes increase and government incentives recede, it is likely that the incremental cost of hybrid vehicles reduces significantly in the near term and provides owner-operators with an increasingly attractive payback period.

3.3. Plug-In Hybrid Electric Technologies

Current Status and Market Opportunities

Plug-in hybrid technology advances the configuration of hybrid electric vehicles discussed earlier: an electric motor and generator are coupled with an engine in a parallel or series architecture. In the case of plug-in technology, however, the battery is generally larger and the user can plug the vehicle in to draw energy from the grid. This is the primary difference in the vehicle design, as the battery is not solely dependent on regenerative braking or the onboard engine for energy.

There are several plug-in hybrid electric trucks in development and the demonstration phase today. For instance, in the LHD market, Bright Automotive is developing a Class 3 plug-in hybrid cargo van with a parallel hybrid architecture. The vehicle will employ a 13 kWh battery pack and a 4 cylinder engine with 2 L displacement. The vehicle will reportedly get about 30-60 miles of all electric range and upwards of 35 mpg fuel economy after the battery is depleted. The vehicle is to be released in the first quarter of 2013.

In the medium heavy-duty sector, Electric Vehicles International (EVI) is leading a project funded by the California Energy Commission to develop a range extended Class 5 plug-in hybrid electric pick-up truck in a series configuration. The development and demonstration team also includes Light Engineering, Valence Technology, and PG&E. To improve the lifecycle impacts of the vehicle's fuel use further, the team is proposing to use liquefied natural gas (LNG) to power an engine, coupled with a 75 kWh battery pack (which weighs about 900 kg). The company forecasts demonstration and in-use testing in 2011, with anticipated ramp up in production to 2019, reaching 3,500 units per year.

In the heavy heavy-duty sector, a team led by Kenworth (a Paccar company) was awarded grant funding by the California Energy Commission to combine Arvin Meritor's dual mode hybrid system with an intercooled recuperated (ICR) microturbine. The dual mode hybrid system from Arvin Meritor provides all-electric operation at low speeds (< 50 mph); at higher speeds (e.g., on the highway) the ICR microturbine replaces the diesel engine.[20] The ICR microturbine has a design point RPM with a maximum shaft efficiency of roughly 44% and exceeds 40% over a range of operating conditions. In contrast, a diesel engine typically exhibits peak efficiency around 45% with a considerably narrower range of operation conditions at near-peak efficiency. Kenworth reports a net cost increase, based on an undisclosed analysis, of $50,000; this cost accounts for the elimination of the diesel engine and associated after-treatment technologies. We assume that the estimate from Kenworth is based on a high volume assumption, considering the battery pack for Arvin Meritor's dual mode hybrid platform likely costs a minimum of $80,000 and the ICR microturbine is more than $100,000.

Vision Motor Corporation entered into an agreement with the Port of Los Angeles to demonstrate a Class 8 fuel cell vehicle; the vehicle has a series hybrid electric architecture with a fuel cell and Li-ion battery pack. The Port has agreed to pay $280,000 for the vehicle; however, we estimate that this is less than the cost of building this vehicle based on the cost of fuel cells and the size of the battery that will be needed for this system. The battery alone is estimated to cost about $85,000. Although not publicly announced, We estimate that the battery on the vehicle is 50-100 kWh.

Plug-in hybrid electric vehicles are suitable for all goods movement applications; the advantage of plug-in hybrid electric systems is that the battery can be sized appropriately to the application. This provides flexibility in vehicle design that will help manufacturers meet the speed, power, and range requirements

[20] The Arvin Merritor dual mode series hybrid configuration should also be considered a viable pathway for the Hybrid Electric Vehicles discussed in the previous section; the battery can be down-sized and the engine can be increased appropriately to power the battery as needed without plug-in capability.

of owner operators. Due to operational requirements and battery technology, the most appropriate markets in the near term will be in the smaller heavy-duty vehicles (e.g., Class 3-5). If the cost and weight of batteries are reduced (discussed in more detail below) via production volume and/or technology advancement, then plug-in hybrid electric vehicles will transition to heavier vehicle classes (e.g., Class 6-8).

Environmental Benefits

The environmental benefits of plug-in hybrid electric vehicles can be significant. For instance, in the case of the Vision Tyrano, there are no tailpipe emissions because the battery is powered by an onboard fuel cell. The more likely designs for vehicles will likely be the hybridized diesel (or natural gas) engine with a battery with lower NOx and PM emissions benefits. In the light-duty sector, emissions benefits are frequently calculated by estimating the vehicle range in all-electric (or charge depleting mode) based on various trip distances. The power and energy requirements of heavy-duty vehicles, however, vary considerably across duty cycles.

To estimate emissions benefits, we assumed a 30 mile all-electric range. Miles driven beyond that threshold are assumed to operate in hybrid mode, including battery power for idle and speeds less 10 mph, gasoline or diesel power for higher speeds, and reduced PM2.5 emissions attributable to regenerative braking.[21] The GHG benefits of plug-in hybrid trucks were calculated using the carbon intensities for gasoline or diesel and the electricity used to power the vehicle. The emissions attributable to the electric miles of operation are calculated using the statewide average carbon intensity reported by ARB in the LCFS (high) and the carbon intensity of marginal electricity supplied to the grid. The GHG emissions attributed to electricity are likely over-estimated due to the Renewables Portfolio Standard which requires utilities to procure a minimum amount of renewable resources. Ultimately, the RPS in California will reduce the carbon intensity of electricity used as a transportation fuel and thereby increase the emissions benefits of vehicle electrification. The estimated emission reductions from plug-in electric trucks are shown in Exhibit 3-9.

Exhibit 3-9. Emissions Benefits of Plug-In Hybrid HDVs (per truck)

Plug-In Hybrid Vehicles	Class 3			Class 6			Class 8b		
	NOx	PM2.5	GHGs	NOx	PM2.5	GHGs	NOx	PM2.5	GHGs
Diesel	75-95%	44-84%	41-51%	58-78%	26-66%	24-36%	28-58%	9-33%	10-25%
Gasoline	68-78%	43-58%	42-52%	43-53%	34-79%	40-50%	N/A	N/A	N/A

Costs

Plug-in hybrid electric vehicles are in the nascent stages of demonstration in the heavy-duty sector. The cost for vehicles is likely to remain high in the near term based on volume production. The most significant cost element of heavy-duty plug-in hybrid trucks will be the battery, which we estimate will be sized between 30-60 kWh depending on the application. We estimate the incremental costs for plug-in electric vehicles shown in Exhibit 3-10.

[21] This assumes full plug in hybrids with sufficient batteries for 30 mile all electric range. Most likely larger heavy duty vehicles will have more limited range due to the high cost of batteries.

Exhibit 3-10. Estimated Commercial Availability and Incremental Costs of Plug-in Hybrid HDVs

Plug-in Hybrid Electric Vehicles	Commercial Availability	Incremental Costs		
		today	2023	2035
Class 3 Step Van / Box Van	2014-2018	$20-30k	$15-25k	$10-20k
Class 6 Box Truck	2016-2020	$30-50k	$25-40k	$20-30k
Class 8b Regional Haul	2016-2020 for ICE/battery hybridization 2017-2022 for fuel cell/battery hybridization	$70-100k	$50-80k	$35-55k

The range of estimates for vehicle costs is larger for plug-in hybrid electric vehicles because of the potential for varying battery sizes. Plug-in hybrids will likely be developed based on vehicle power demands, with the battery designed to maximize the utility of the hybridization. This right-sizing will also depend on estimates of what owner operators are willing to accept in the market; as a result, even vehicles in the same application (e.g., Class 6 box truck) may have considerably different incremental costs.

Plug-in electric vehicles will require significant charging infrastructure investments. Today, there are three levels of charging that the industry uses to characterize electric vehicle service equipment (EVSE) i.e., chargers. Level 1 is essentially a standard cord and plug at a home or business. With an estimated power delivery of 1-2 kW, it cannot charge a heavy-duty plug-in electric vehicle in sufficient time to warrant consideration. The other two types of charging are:

- **Level 2** charging employs a permanently wired EVSE that is operated at a fixed location. This equipment is used specifically for EV charging and is rated at less than or equal to 240 V AC, and less than or equal to 80 A. Level 2 charging service also requires additional grounding, personal protection system features, a no-load make/break interlock connection, and a safety breakaway for the cable and connector. If 240 V service is not already installed at the site, a new service drop will be required from the utility. With 40 A, 240 V service power can be delivered at 7.5 kW.
- **DC Fast Charging** employs a permanently wired EVSE, operated at a fixed location, specifically for EV charging and is rated at greater than 19.2 kW. Level 3 charging or fast charging typically uses an off board charge system serviced by a 480 V three phase circuit or DC power. Equipment size could vary from 60 to 150 kW. Manufacturers may include a fast-charge connection in addition to Level 1 or Level 2 charging connections on most EVs, giving owners the option of quickly recharging their vehicles.[22] At this point, there is no industry (i.e., SAE) standard for DC Fast Charging.

Exhibit 3-11 provides recent costs estimates for charging stations.

[22] S Chhaya, S., and M Alexander, *Plug-In Electric Vehicle Infrastructure Installation Guidelines Volume 1: Multi-Family Dwellings*, EPRI 1017682, September 2009

Exhibit 3-11. Estimates of Electric Vehicle Charging Stations

Charger Level	Application	Notes/Details	Installed Cost	Source
2	Non-residential	Facility Charging	$1,852	a
		Public	$2,000-$3,000, up to $5,000	b
			$2,500-$4,000	c
			$6,341	d
			$4,468	e
			$8,048	e
DC fast charge (Level 3)	Non-residential	Public, 2 charge points	$65,000	e
		Public	$75,000	f

[a] *Plug-in Hybrid Electric Vehicle Charging Infrastructure Review*, Kevin Morrow, *et al*, Final Report Battelle Energy Alliance Contract No. 58517, November 2008
[b] *Electrification Roadmap, Revolutionizing Transportation and Achieving Energy Security*, Electrification Coalition, November 2009
[c] "A Car Charging Infrastructure Takes Shape", John Lorinc, New York Times, June 16, 2009
[d] CPUC Order Instituting Rulemaking (OIR) to Consider Alternative-Fueled Vehicle Tariffs, Infrastructure and Policies to Support California's Greenhouse Gas Emissions Reduction Goals
[e] *Electric Vehicle Charging Infrastructure Deployment Guidelines for the Oregon I-5 Metro Areas of Portland, Salem, Corvallis and Eugene*, Electric Transportation Engineering Corporation (eTec), January 2010; information also obtained from eTec representative at PHEV 2010 Expo, San Jose, CA July 27, 2010
[f] Electric Truck Demonstration Fact Sheet, Port of Los Angeles, available online at: http://www.portoflosangeles.org/DOC/Electric_Truck_Fact_Sheet.pdf

Barriers to Advancement

Plug-in hybrid configurations using a battery will face barriers regarding the cost and lifetime of the battery. The barriers to advancement highlighted here regarding battery technology are similar to those for battery electric vehicles in the heavy-duty sector (next section); however, the barriers are more significant in the pure battery electric category.

The plug-in hybrid configurations using a fuel cell and a battery face many barriers, including: the cost of the battery, the cost of the fuel cell system, the availability of hydrogen, and onboard hydrogen storage. These are all significant barriers, particularly on the cost side.

The **cost of batteries** is the most significant impediment for heavy-duty vehicles. Several studies have estimated current battery pack costs and projected cost reductions into the future.[23] These studies are generally looking at battery packs for plug-in hybrid electric light duty vehicles, a much different application than what would be considered for a goods movement strategy. Nonetheless, there are not comparable studies for medium- or heavy-duty applications. Generally, we can assume that projected cost reductions for batteries used in the light-duty sector will a) occur faster, and b) be more significant based on factors such as size, production volume, and power density.

The costs reported here are based on nameplate ratings of battery packs in kWh, as opposed to useable battery charge. Typically, a battery is operated over a limited range of its nameplate capacity, ranging

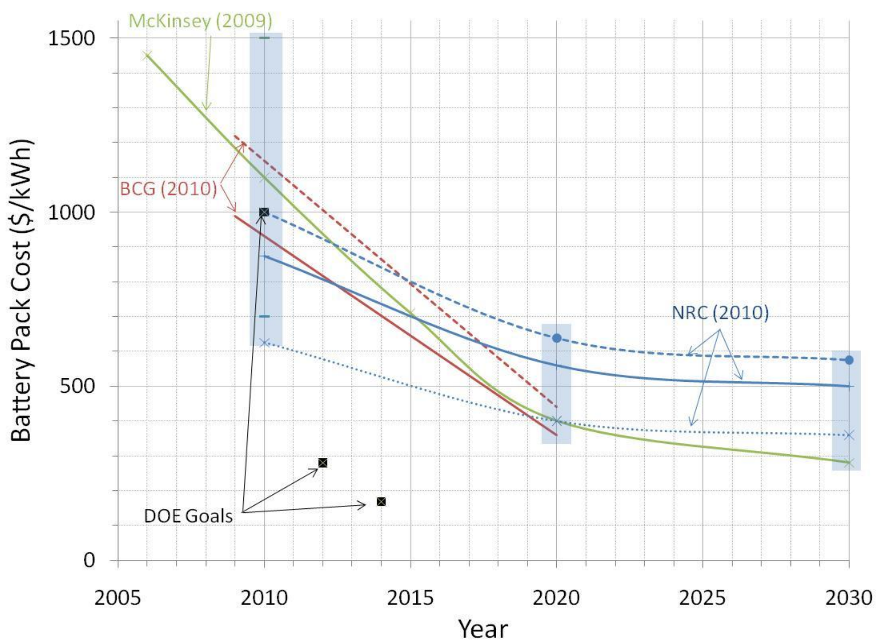
[23] E.g., Nelson, PA; Santini, DJ; Barnes, J. *Factors Determining the Manufacturing Costs of Lithium-Ion Batteries for PHEVs*, EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium, Stavanger, Norway, May 2009.

from 50% in more conservative scenarios up to 80% in more stable and aggressive scenarios. Over time, as the technology advances and stability is improved, automakers will trend towards the higher useable rate.

- A recent report by the National Research Council estimates a current range of battery packs for Li-ion batteries as $500/kWh up to $1500/kWh (see Exhibit 3-, blue lines).[24] Without any major technological breakthroughs i.e., a shift to different battery chemistry, the NRC estimates a 35% reduction in the cost of Li-ion batteries by 2020 and a 45% reduction by 2030.
- Analysts at McKinsey report a similar range of costs for vehicles today, ranging from $650/kWh to $1500/kWh.[25] McKinsey estimates a continued decrease in batteries between now and 2020 (green line, Exhibit 3-), and out to 2030; their assumptions are generally based on an increase in production volumes, a "projected breakthrough for materials and/or productivity", and improvements in the battery's state of charge window.
- The BCG report estimated costs today between $1000 and $1200/kWh.[26] They predict that costs will decline "steeply" as production volumes increase and that individual parts will become less expensive with experience and scale effects. They also attribute some reductions to automation, leading to reduced scrap levels and labor costs.
- Note the DOE has set goals for the cost of Li-ion battery packs: $280/kWh and $168/kWh in 2012 and 2014, respectively.[27]

The values from these analyses and DOE's targets are shown in Exhibit 3-12.

Exhibit 3-12. Estimated Reductions in Battery Costs ($/kWh, nameplate)



[24] National Research Council, *Transitions to Alternative Transportation Technologies--Plug-in Hybrid Electric Vehicles*, 2010

[25] Hensley, R; Knupfer, S; Pinner, D. *Electrifying cars: How three industries will evolve*, McKinsey Quarterly, 2009.

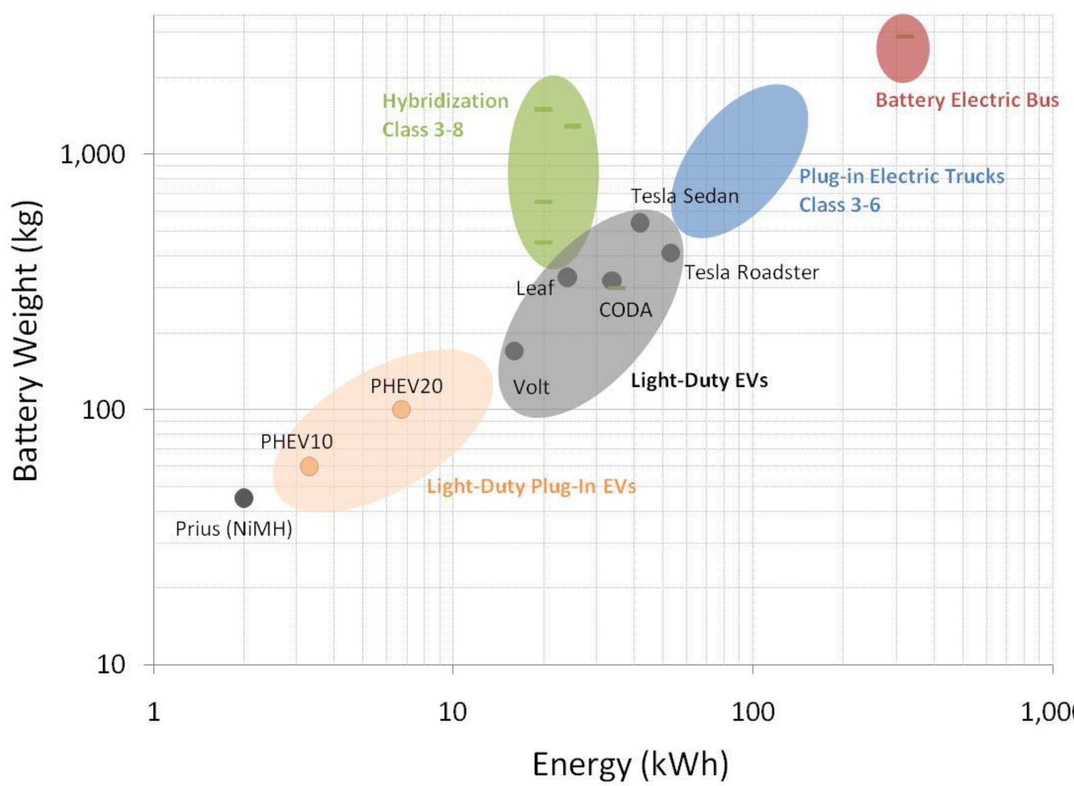
[26] Boston Consulting Group. *Batteries for Electric Cars – Challenges, Opportunities and the Outlook to 2020*, 2010.

[27] United States Advanced Battery Consortium and FreedomCAR, *Electrochemical Energy Storage Technical Team: Technology Development Roadmap*, July 2006.

Battery cost reductions are a controversial subject. Both McKinsey and BC estimate up to 50%, reductions. However, the NRC report lists several reasons to be skeptical about cost reductions in the near term (i.e., 2020). For instance, the common refrain regarding economies of scale is not as convincing considering the volume of Li-ion battery production worldwide; more factories will not necessarily reduce the cost(s). The NRC report considers Li-ion technology sufficiently advanced that cost reductions from technological breakthroughs are unlikely; incremental improvements are far more likely. It is also worth noting that the materials from which the batteries are comprised account for some 25-50% of the cost, which is unlikely to change significantly.

The **weight of batteries** is also a significant concern in goods movement. While this is not a major concern in applications such as transit buses or refuse haulers, for goods movement the added weight can decrease fuel economy and reduce the payloads that trucks can carry (thereby decreasing profitability). In long-haul applications, battery electric vehicles seem highly unlikely without significant breakthroughs in battery chemistry. Exhibit 3-13 displays battery energy and battery weight for applications today. The orange and grey ovals and corresponding dots represent plug-in hybrid electric vehicles and battery electric vehicles in the light duty sector. The green oval represents the anticipated range of battery weight and energy in a full hybridization scenario (as opposed to what is termed a "mild" hybridization using a smaller battery pack). The blue oval is ICF's estimate for the energy requirements and corresponding battery weight for plug-in electric trucks up to Class 6. The red oval to the far right represents the estimated weight and energy of a battery needed to electrify a transit bus or a Class 8 regional haul truck. Note that the 320 kWh nameplate battery is expected to weigh upwards of 3 metric tons (6,600 lbs).

Exhibit 3-13. Battery Energy (kWh) vs. Battery Weight (kg)

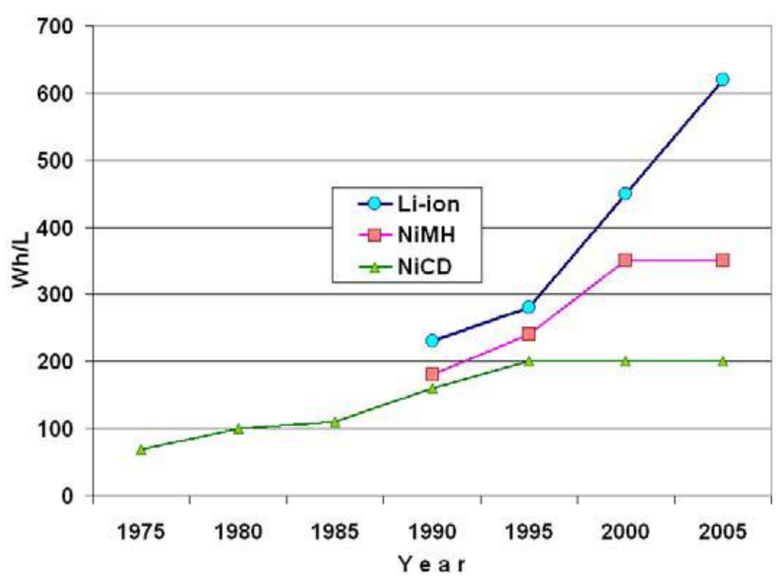


Lightweight materials will be used to reduce fuel consumption; however, this weight reduction is unlikely to offset the increases from large battery packs, particularly in battery electric configurations. In mild hybridization scenarios, the weight increase is likely marginal; however, it will become more significant in a full hybridization or plug-in hybrid configuration.

The **life of the battery and the associated warranty** are both issues of concern for goods movement. Based on the VMT characteristics of LHD, MHD, HHD trucks, the battery will likely be deep cycled every day. A conservative lifetime of 15 years will require 4,000-5,000 deep cycles; today's batteries are rated closer to 2,000 deep cycles. Although battery improvements are likely over the next several years, the all electric range of plug-in configurations will be limited until these lifecycle issues are addressed. A typical warranty for batteries may range from 5-8 years or by the number of cycles. Note that for stop-and-go applications, the battery may need to be recharged frequently as the vehicle will operate in charge depleting mode frequently. Similarly, in long-haul applications, the vehicle may need multiple (fast) recharges.

There are new battery chemistries that may improve power and/or energy density, reduce weight, and improve the life of the battery in the long-term; however, these are in the research and development phase. Initial electric vehicles relied on batteries based on lead acid and zinc bromine chemistry; the original Toyota Prius and other hybrid models today use nickel metal hydride (NiMH) chemistry; the extended range electric vehicles and all electric vehicles to be released at the end of 2010 and into 2011 use lithium ion (Li-ion) batteries. Note that it took some 30 years of development for the transition to Li-ion batteries to occur. As recently as 2000, an Argonne National Laboratory report (Gaines and Cuenca, 2000) stated that these "batteries are well on their way to meeting the challenging technical goals that have been set for vehicle batteries. However, they are still far from achieving the current cost goals." Exhibit 3-14 is a useful reference to demonstrate how previous battery chemistries, NiMH and Nickel Cadmium, have reached a plateau in energy density. The question today is whether or not the Li-ion battery chemistry has reached its energy density plateau? And if so, what are the cost implications?

Exhibit 3-14. Battery Evolution: Chemistry and Energy Density (Wh/L)



Source: Shinsuke Ito, EVS-22 Plug-In Hybrid Electric Vehicle Workshop

Potential for Advancement

Plug-in hybrid trucks are likely to be introduced at more significant levels in the next 3-5 years, based on the current status of demonstration projects. There is significant potential for plug-in hybrid electric vehicles in the heavy-duty sector in the next 3-10 years, across all sectors. Some of the reasoning behind the potential for plug-in hybrid trucks is highlighted here:

- The hybridized configuration is a compromise between the cost and weight tradeoffs of a pure battery electric truck or vehicle (discussed in more detail below).
- The hybridization of the power train also decreases the cycles on the battery, thereby extending its useful life (in years, not deep cycles) through less taxing use.
- The increase in so-called mild hybridization and full hybridization in the heavy-duty sector, driven by government incentives such as the HVIP as well as fuel economy and GHG regulations, will enable the transition to plug-in capable vehicles in the heavy-duty sector.
- The duty cycle and operational characteristics of the light and medium heavy-duty vehicles are prime candidates for this technology.
- Plug-in technologies require only minor infrastructure modifications as they will likely use available liquid or gaseous fuels for the on-board engine, but will require some build out of electric charging infrastructure.

3.4. Battery Electric Technologies

Current Status and Market Opportunities

Battery electric vehicles replace the entire engine and drive train of a conventional vehicle with an electric motor and generator, powered by a battery pack. Electric vehicles have a number of advantageous characteristics such as: high torque over a broad range of speeds leading to smoother operation; lower maintenance costs due to fewer moving parts than a conventional combustion engine vehicle; potential for reduced operating costs depending on the price of electricity and the displaced fuel; zero tailpipe emissions and reduced greenhouse gas emissions on a lifecycle basis; and energy security via petroleum displacement.[28]

The recent increase in electric vehicle offerings is a result of advances in Lithium-ion battery technology. Previously, the most common battery technology used was a Nickel Metal Hydride (NiMH) chemistry. Battery electric vehicles are positioned to make small significant gains in the light-duty vehicle sector over the next several years with the potential for much greater penetration in the mid- to long term. Some of the developments in heavy-duty sector, with an emphasis on goods movement, are highlighted in this section.

In the LHD sector, Navistar recently released the all-electric eStar, a Class 3 delivery truck. The truck can travel approximately 100 miles on a single charge at a maximum speed of 50 mph. The eStar has received EPA's clean-fuel fleet vehicle certification and ARB's certification as a zero-emission vehicle. The vehicle includes an 80 kWhr lithium ion battery cassette which powers a 70 kW motor. The battery can be charged in 6-8 hours, or a depleted battery cassette can be replaced with a charged battery cassette in about 20 minutes. The eStar is based on a product developed by Modec, a company based in the UK. Modec offers two types of batteries in its vehicle: a) a Zebra battery with 85 kWh of energy, a molten salt battery based on sodium nickel chloride chemistry, providing about 100 miles of range; and b) a lithium-ion battery pack rated at 52 kWh with a 60 mile rage. In both cases the battery pack is designed to be swapped in less than 20 minutes for continuous operations. Modec recently went into administration, which is akin to filing for Chapter 11 bankruptcy in the United States. The manufacturer reports that only

[28] California Energy Commission, *Full Fuel Cycle Assessment, Well to Wheels Energy Inputs, Emissions, and Water Impacts*, Prepared by TIAX, LLC, 2007.

9 vehicles were sold in the United States in 2010, well below the target of 400. In fact, the manufacturer reports that only 400 vehicles have been produced since the firm's launch in 2007. There were talks of Modec being acquired by Navistar, however, those talks fell apart in February 2011.

Smith Electric Vehicles offers the Edison and the Newton. The Edison comes in a panel van or minibus application, powered with a Lithium-ion battery pack ranging from 36-50 kWh, depending on the configuration. The Edison is not currently available in the United States. The Newton electric vehicles come in three sizes ranging in GVWR from 16,500-26,500 lbs (i.e., in the MHD range). The Newton includes a battery back of 80 kWh or 120 kWh which power a 120 kW induction motor, achieving a range of 100-150 miles, and can be charged in 6-8 hrs. The vehicle achieves a maximum speed of about 50 mph.

Balqon Corporation has three heavy-duty vehicle offerings: the Nautilus XE20, XE30 and the Mule M150. The company's yard hostler, Nautilus XE20, has a range of 95 miles and a maximum speed of 25 mph (unloaded conditions). The Nautilus XE30 is an on-road vehicle for short haul applications (Class 7 and Class 8) with a maximum speed of 45 mph. The Nautilus XE20 and XE30 use a 140 kWh and 250 kWh battery pack, respectively. The batteries are rechargeable in 6-7 hours with a 40 kW charger. The Mule M150 is an on-road delivery vehicle with a top speed of 55 mph and a range of about 150 miles unloaded and 90 miles loaded; the battery pack is 280 kWh. In 2008, the City of Los Angeles entered a contract with Balqon Corporation to test 20 all electric terminal tractors or yard hostlers and 5 on-road drayage trucks for short-haul applications. The City reportedly paid $189,950 per yard hostler and $208,500 for the on-road truck with the expectation of receiving the trucks by December 2009. As of March 2011, Balqon had delivered 14 of the yard hostlers and 1 of the on-road drayage trucks. .

There are several promising energy storage technologies that may improve the value proposition of battery electric vehicles. There will likely be small and incremental near term improvements (over the next 5 years); however, energy storage improvements that markedly improve the price parity of heavy-duty battery electric vehicles with conventional vehicles are more likely to occur over the long term (on the order of 10-30 years).

- Improved lithium-ion batteries: There are many incremental improvements that are likely to be made to Li-ion batteries over the next several years. For instance, replacing the anode material – generally carbon and/or graphite – with nanostructures e.g., silicon nanoparticles, may increase the power density and cycling life of Li-ion batteries by 5-10 times their current levels. Similarly, advances in cathode materials may allow for faster re-charging, effectively combining the discharge/recharge benefits of an ultracapacitor with the energy storage benefits of a battery. In both cases, these technologies have been demonstrated and tested at a bench scale and are at least 5-10 years away from applications in electronics (sooner) or vehicles (later).
- Batteries coupled w/ Ultracapacitors: The primary benefit of ultracapacitors is their fast charge and discharge profile (i.e., high specific power), compared to batteries. They also tend to have a longer life than batteries and are less likely to degrade over time. The downside of ultracapacitors, however, is that they have a very low energy density profile, as much as 100 times lower than some Li-ion configurations. When batteries are coupled with ultracapacitors, the goal is generally to have the ultracapacitor help meet the peak power (i.e., acceleration) demands of vehicles, thereby reducing the load on the battery and extending the useful battery capacity or state of charge. Coupled battery/ultracapacitor systems will likely develop in the hybrid and plug-in hybrid configurations before the battery electric configurations. However, these configurations could go a long way to reducing the weight and range concerns of battery electric vehicles in the heavy-duty sector because they can help downsize the battery and increase its useful life.
- Metal Air batteries: Metal air batteries use a metal at the anode (e.g., Zinc or Lithium) and a porous structure with catalytic properties at the cathode for the oxidation reaction. The oxygen for the reaction

is supplied from the air, hence the battery's distinction. The batteries have an energy density of some 3-10 times Li-ion batteries. Currently the main limitations of this technology are the life of the battery and the recharging limitations. It is reported that metal air batteries become inoperative at hundreds of charge/depleting cycles, far below the thousands needed for a vehicle application. Furthermore, the batteries cannot be charged or discharged quickly, which is limiting for regenerative braking and acceleration applications in vehicles.

The range of battery electric vehicles is dependent on the battery technology and the size of the battery pack. The range of battery electric vehicles in the HD sector could reach 50-100 miles with appropriate sizing; however, these ranges are generally achievable at low speeds (discussed further below). Battery electric vehicles can be sized appropriately and include a sufficient motor to meet the power and torque requirements of heavy-duty vehicles; however, at high speeds, existing battery technology will be depleted due to the energy per mile requirements of heavy-duty vehicles. The LHD-2, MHD, and HHD classes average about 70, 85, and 300 miles per day in the South Coast Air Basin. Based on these ranges, the HHD category is the most limited and the vehicle would likely need several recharges over the course of a day or battery swap capabilities.

The speed of all-electric vehicles is also limited at this time due to battery constraints. The vehicle's range, battery life, and weight have been optimized at the expense of vehicle speed. For instance, the Navistar eStar all-electric van has a top speed of about 50 mph and cannot be driven on the highway. Balqon battery electric trucks and the Smith electric trucks also have relatively low maximum speeds, ranging from 25-50 mph.

The added weight for battery electric vehicles will also be a concern in the goods movement sector. The NRC report estimates that that the weight added for various hybridization scenarios ranges from 350-1500 lbs of added weight in Class 3-8 vehicles. Although battery electric vehicles will enable the removal of more components (e.g., an engine), the batteries used will likely be 50-100 times heavier than the batteries in mild hybridizations for the heavy-duty sector (see Exhibit 3-13).

Emissions Benefits

Battery electric trucks produce zero tailpipe emissions. They will still generate a small amount of PM2.5 due to tires and brakes. The PM2.5 emissions benefits reported include the benefits of regenerative braking mentioned previously. The GHG emissions are reported using statewide average carbon intensities for electricity (high) and the marginal carbon intensity for electricity (low). As noted previously, these emissions are likely over-estimated due to the Renewables Portfolio Standard which requires utilities to procure a minimum amount of renewable resources. Ultimately, the RPS in California will reduce the carbon intensity of electricity used as a transportation fuel and thereby increase the emissions benefits of battery electric trucks.

Exhibit 3-15. Emissions Benefits of Battery Electric HDVs (per truck)

Battery ElectricVehicles	Class 3			Class 6			Class 8b		
	NOx	PM2.5	GHGs	NOx	PM2.5	GHGs	NOx	PM2.5	GHGs
Diesel	100%	74-82%	51-59%	100%	90-98%	51-59%	100%	76-84%	51-59%
Gasoline	100%	58-66%	52-60%	100%	60-68%	52-60%	N/A	N/A	N/A

Costs

We estimate significant incremental vehicles costs for battery electric vehicles, based on the cost of the battery. The incremental costs of this technology are expected to remain high even out to 2035. The estimated incremental costs of battery electric HDVs are shown in Exhibit 3-16.

Exhibit 3-16. Estimated Commercial Availability and Incremental Cost of Battery Electric HDVs

Battery Electric Vehicles	Commercial Availability	Incremental Costs		
		today	2023	2035
Class 3 Step Van / Box Van	2015-2018	\$30-50k	\$25-40k	\$15-30k
Class 6 Box Truck	2017-2022	\$40-60k	\$30-45k	\$20-30k
Class 8b Regional Haul	2020-2025	\$100-135k	\$80-110k	\$50-75k

Barriers to Advancement

The most significant barrier to advancement for battery electric trucks in the HD sector is the battery; these barriers were discussed in more detail in the previous section. The same concerns highlighted in the previous section exist for battery electric vehicles, however, they are even more severe. For instance, the cost of a battery to power a Class 5 medium duty vehicle (e.g., Ford F-550) is more than \$80,000. The battery pack for an all-electric bus is more than \$200,000. The duty cycle requirements for the heavy-duty sector (classes 3-8) are considerably more demanding than the light-duty sector, which is experiencing a dramatic increase in the number of battery electric vehicle offerings.

Another barrier for battery electric vehicles will be the availability of charging infrastructure. The infrastructure required to charge thousands of heavy-duty battery electric vehicles will be significant. Furthermore, based on existing and projected vehicle ranges, it is likely that multiple charges per vehicle will be needed throughout the day to meet range requirements, particularly for HHD vehicles. Most studies demonstrate that the potential negative impacts of charging light-duty electric vehicles can be mitigated using a combination of night-charging and smart-charging. However, there is little research into the potential impacts of frequent heavy-duty vehicle charging. The impacts are likely to be significant given the likelihood of fast charging to maintain operability during a standard work shift, and the power requirements of large batteries in HD electric vehicles.

Potential for Advancement

Battery electric trucks have limited potential in the near to mid-term based on some of the following highlighted issues:

- There are several cost limitations of batteries that limit the potential of electric vehicles in the heavy-duty sector. The incremental cost of the vehicle is high at this point – estimated at as much as \$120,000 for a Class 8 vehicle. Furthermore, the operational savings realized from using electricity instead of diesel are unclear at this time. Most estimates for savings are based on a lower electricity rate (\$/kWh) than what will likely be charged by utilities. The confounding factor is that in the near term, heavy-duty vehicles will likely need fast charges requiring more power and likely during a shift as opposed to night-time charging. The costs of day-time charging may exceed estimates significantly. Finally, the operational savings are dependent on the battery maintaining a certain useable capacity.

With warranties of batteries in the 3-5 year range and operational design at double that, with a maximum of about 10 years, the life cycle costs of operating a battery vehicle may include replacing an expensive battery at or prior to the vehicle's half-life. This is an expensive proposition that introduces a considerable uncertainty into a fleet's purchasing decision. In addition to the cost uncertainty, there is technical uncertainty associated with inserting identical or sufficiently similar battery technology 5-10 years after the vehicle was originally manufactured.

- The lifetime of the battery is a significant concern at this point. As mentioned above, most batteries have limited warranties for only a fraction of the likely lifetime of many goods movement applications.
- The weight of batteries will be a concern for the heavy-duty goods movement sector. The potential increase in weight can reduce the payload of the vehicle and thereby the economics of operation. In all-electric vehicles, the weight increase is obviously offset by removing other components e.g., the engine. Using current Lithium ion battery technology, a 250 kWh capacity battery weighs approximately 4,000 lbs.
- The financial condition of many of the leading firms in the heavy-duty electric vehicle market is cause for concern. In addition to the financial troubles of Modec highlighted previously, Balqon has disclosed in financial statements that the shortage of cash on hand to continue operations is a going concern. Similarly, another electric vehicle manufacturer, ISE, a manufacturer of hybrid and electric powertrains for buses, filed for bankruptcy in August 2010, just 6 months after raising about $20 million via an initial public offering on the Toronto Stock Exchange.

In the near term, the lighter heavy-duty vehicle classes (e.g., Class 3 and Class 4) have moderate potential for battery electric vehicles in the next 3-5 years, with similar potential in the Class 5-6 vehicles, on a longer time scale of 5-7 years. However, the potential for significant penetration into the Class 7 and Class 8 market is low at this time without better-than-incremental improvements in battery technology. This conclusion is similar to that voiced in the Ports' recent zero emission technologies roadmap, which notes: "Current battery technologies do not provide adequate range at a reasonable cost. While efforts are being made to improve battery technologies, no cost-effective options are expected to become available for the Class 8 truck application in the near term."[29]

3.5. Summary of Environmental Benefits and Costs

Exhibit 3-17 summarizes the advanced truck technology strategies for emission reduction, including barriers and emissions benefits. Plug-in hybrids and battery electric vehicles offer the potential for the largest emission reduction, but have higher costs and will not be commercially available on a large scale for five to ten years.

[29] Port of Long Beach and Port of Los Angeles, *Roadmap for Moving Forward with Zero Emission Technologies at the Ports of Long Beach and Los Angeles*, Technical Report, Updated August 2011.

Exhibit 3-17. Summary of Advanced Truck Technology Strategies Barriers and Benefits

Technology		Potential	Barriers		Commercial Availability	Emission Benefits		
			Vehicle	Fuel		NOx	PM2.5	GHGs
Advanced Nat. Gas Vehicles	NG HD Engines	medium	limited offerings incremental cost	infrastructure availability (NG) sustained low NG prices	today	20-50%	0-30%	20-38%
	HCNG	low		infrastructure availability dependent on transition to H2 fuel cells	2015-18	30-70%	20-40%	25-43%
Hybrid Vehicles	Hybrid Electric	high	incremental cost	--	today	8-62%	4-45%	5-35%
	Hydraulic Hybrid	medium	incremental cost best in stop-and-go applications	--	2015			
Plug-In Hybrid Vehicles	ICE / Battery	medium	battery cost battery weight battery lifetime	grid impacts of fast charging infrastructure	2014-20	28-95%	9-85%	10-52%
	Fuel Cell / Battery	low	cost of fuel cell + battery on-board storage of fuel vehicle weight	infrastructure availability (H_2)	2017-22	100%	58-98%	51-80%
Battery Electric Vehicles		low-medium	vehicle range battery cost battery vehicle battery lifetime	grid impacts of fast charging infrastructure	2015-25	100%	58-98%	51-60%

In order to assess the potential emissions benefits of the truck technology strategies and associated costs, we developed scenarios that assume maximum possible deployment of each technology. These scenarios are purely hypothetical and probably unrealistic, but serve to allow comparison across the technologies and vehicle class/fuel type categories. The emissions benefits and costs can be scaled (e.g., one-tenth the investment would achieve approximately one-tenth the emission reduction).

To develop these scenarios, we estimated the first year the technology *could be* commercially available on a large scale for each weight class, as discussed in the sections above. In some cases, this assumes that major government incentive programs would cause manufacturers to increase production beyond what is expected to serve baseline demand. Beginning in the first year of availability, the scenarios assume that all new trucks sold in a weight class employ the technology. For example, natural gas trucks for the LHD sector are commercially available today; for the natural gas technology scenario, we therefore assume that all new LHD trucks sold beginning in 2012 are natural gas. Similarly, we assume that battery electric trucks for the MHD sector would be available on a large scale beginning in 2020; for the battery electric scenario, we assume that all new MHD trucks sold beginning in 2020 are battery electric.

The vehicle cost estimates reflect *incremental costs* (the difference between an advanced technology vehicle and the comparable conventional technology vehicle), as discussed in the sections above. Thus, we assume that fleets would purchase advanced technology trucks at the same rate they would otherwise purchase conventional trucks, provided the incremental costs are subsidized.

Extensive deployment of natural gas, plug-in hybrid vehicles, or battery electric vehicles will likely require public investment in fueling/charging infrastructure. These costs are estimated assuming a minimum number of stations or chargers required to ensure that trucks in the goods movement sector can refuel or charge when needed, without significantly modifying driver behavior or logistics, using the following assumptions:

- For natural gas vehicles, we assumed a throughput of 10,000-12,500 gallons (diesel gallon equivalents) per day per station and estimated the number of stations that would be required to fuel the number of vehicles in each scenario. We assumed a cost of $2 million for each station.
- We assumed a mix of Level 2 and DC fast chargers in the plug-in hybrid vehicle scenario and the battery electric vehicle scenario, with one exception. For heavy heavy-duty battery electric vehicles, we assumed that fast chargers would be required based on the size of batteries needed to charge the vehicle.

The following exhibits show the results of our emissions benefits and cost estimation calculations. Exhibit 3-18 shows, for an individual truck, the emission reduction benefits (NOx, PM2.5, and GHGs), estimated commercial availability, and incremental costs by vehicle class and by advanced vehicle technology. The resulting emission reductions and costs for each of the scenarios are shown in Exhibits 3-19 (for 2023) and 3-20 (for 2035). Exhibits 3-19 and 3-20 also indicate the market penetration of each advanced vehicle technology based on a) when the technology was estimated to be commercially available and b) assuming that those vehicles represent 100% of new vehicles sold as soon as they are commercially available. Note that for a given truck class and fuel, the results are mutually exclusive. For example, the benefits and costs of Natural Gas LHD1 Gasoline cannot be combined with other technologies for LHD1 Gasoline trucks.

Exhibit 3-18. Advanced Truck Technology, Benefits, Availability, and Incremental Costs (reported on a Per Truck Basis)

Technology			NOx reduction		PM2.5 reduction		GHG reduction		Availability	Incremental Cost	
	Class	Fuel	low	high	low	high	low	high		2023	2035
Natural Gas	LHD1	G	20%	30%	0%	0%	21%	38%	2012	$17,000	$13,600
		D	20%	30%	10%	30%	20%	37%	2012	$17,000	$13,600
	LHD2	G	20%	30%	0%	0%	21%	38%	2012	$17,000	$13,600
		D	20%	30%	10%	30%	20%	37%	2012	$17,000	$13,600
	MHD	G	25%	35%	0%	0%	21%	38%	2012	$30,000	$24,000
		D	25%	35%	10%	30%	20%	37%	2012	$30,000	$24,000
	HHD	D	35%	50%	10%	30%	20%	37%	2012	$40,000	$32,000
Hybrid Electric	LHD1	G	11%	21%	21%	31%	20%	35%	2012	$12,000	$8,000
		D	42%	62%	25%	45%	20%	35%	2012	$12,000	$8,000
	LHD2	G	11%	21%	21%	31%	20%	35%	2012	$12,000	$8,000
		D	42%	62%	25%	45%	20%	35%	2012	$12,000	$8,000
	MHD	G	8%	18%	21%	31%	20%	35%	2012	$35,000	$20,000
		D	36%	56%	9%	29%	20%	35%	2012	$35,000	$20,000
	HHD	D	31%	41%	4%	24%	5%	20%	2014	$55,000	$40,000
Plug-In Hybrid	LHD1	G	68%	78%	43%	58%	42%	52%	2016	$18,500	$12,500
		D	75%	95%	45%	85%	41%	51%	2016	$18,500	$12,500
	LHD2	G	68%	78%	43%	58%	42%	52%	2016	$22,000	$17,500
		D	75%	95%	45%	85%	42%	52%	2016	$22,000	$17,500
	MHD	G	43%	53%	34%	49%	40%	50%	2018	$35,000	$25,000
		D	58%	78%	29%	69%	24%	36%	2018	$35,000	$25,000
	HHD	D	28%	58%	9%	33%	10%	25%	2020	$70,000	$50,000
Battery Electric	LHD1	G	100%	100%	58%	66%	52%	60%	2017	$27,500	$17,500
		D	100%	100%	74%	82%	51%	59%	2017	$27,500	$17,500
	LHD2	G	100%	100%	58%	66%	52%	60%	2017	$32,000	$20,000
		D	100%	100%	74%	82%	51%	59%	2017	$32,000	$20,000
	MHD	G	100%	100%	60%	68%	52%	60%	2020	$37,000	$25,000
		D	100%	100%	90%	98%	51%	59%	2020	$37,000	$25,000
	HHD	D	100%	100%	76%	84%	51%	59%	2023	$95,000	$62,500

Exhibit 3-19. Advanced Truck Technology Scenario Benefits in 2023

			NOx (tpd)					PM2.5 (tpd)					GHG (tpd)					Penetration	Cost (Millions)	
			SCAB Baseline	Reduction		% of Baseline		SCAB Baseline	Reduction		% of Baseline		SCAB Baseline	Reduction		% of Baseline				
Tech.	Class	Fuel		low	high	low	high		low	high	low	high		low	high	low	high		Vehicles	Infrast.
Natural Gas	LHD1	G	11.84	1.57	2.36	13%	20%	0.158	0.000	0.000	0%	0%	7,101	991	1794	14%	25%	56.7%	$1,646	$64
		D	4.54	0.58	0.87	13%	19%	0.060	0.003	0.012	5%	19%	1,167	150	278	13%	24%	55.0%	$374	$9
	LHD2	G	2.27	0.32	0.48	14%	21%	0.032	0.000	0.000	0%	0%	1,483	217	393	15%	26%	59.6%	$362	$14
		D	3.10	0.42	0.63	14%	20%	0.040	0.002	0.008	5%	20%	768	105	194	14%	25%	57.3%	$261	$6
	MHD	G	2.06	0.39	0.55	19%	27%	0.026	0.000	0.000	0%	0%	1,093	175	316	16%	29%	60.0%	$427	$10
		D	7.43	1.74	2.44	23%	33%	0.623	0.053	0.175	9%	28%	11,737	2202	4073	19%	35%	91.3%	$2,286	$153
	HHD	D	44.93	14.79	21.13	33%	47%	1.657	0.128	0.469	8%	28%	30,340	5707	10558	19%	35%	88.4%	$1,810	$397
	Total		*76.15*	*19.82*	*28.46*	*26%*	*37%*	*2.596*	*0.186*	*0.664*	*7%*	*26%*	*53,690*	*9546*	*17605*	*18%*	*33%*		*$7,165*	$653
Hybrid Electric	LHD1	G	11.84	0.87	1.66	7%	14%	0.158	0.022	0.032	14%	21%	7,101	944	1652	13%	23%	56.7%	$1,162	$0
		D	4.54	1.22	1.80	27%	40%	0.060	0.010	0.017	16%	29%	1,167	150	263	13%	22%	55.0%	$264	$0
	LHD2	G	2.27	0.18	0.33	8%	15%	0.032	0.005	0.007	15%	22%	1,483	207	362	14%	24%	59.6%	$255	$0
		D	3.10	0.88	1.31	28%	42%	0.040	0.007	0.012	17%	31%	768	105	183	14%	24%	57.3%	$184	$0
	MHD	G	2.06	0.12	0.28	6%	13%	0.026	0.004	0.006	16%	23%	1,093	166	291	15%	27%	60.0%	$498	$0
		D	7.43	2.48	3.87	33%	52%	0.623	0.053	0.170	9%	27%	11,737	2202	3853	19%	33%	91.3%	$2,667	$0
	HHD	D	44.93	11.66	15.46	26%	34%	1.657	0.053	0.335	3%	20%	30,340	1285	5138	4%	17%	75.7%	$2,131	$0
	Total		*76.15*	*17.40*	*24.71*	*23%*	*32%*	*2.596*	*0.154*	*0.580*	*6%*	*22%*	*53,690*	*5058*	*11742*	*9%*	*22%*		*$7,161*	*$0*
Plug-In Hybrid	LHD1	G	11.84	4.03	4.62	34%	39%	0.158	0.034	0.046	21%	29%	7,101	1475	1824	21%	26%	39.1%	$1,236	$131
		D	4.54	1.64	2.08	36%	46%	0.060	0.013	0.025	22%	41%	1,167	232	289	20%	25%	38.2%	$283	$30
	LHD2	G	2.27	0.83	0.95	37%	42%	0.032	0.007	0.010	23%	31%	1,483	332	410	22%	28%	42.3%	$332	$30
		D	3.10	1.22	1.54	39%	50%	0.040	0.009	0.018	24%	45%	768	168	208	22%	27%	40.9%	$241	$21
	MHD	G	2.06	0.40	0.50	20%	24%	0.026	0.004	0.006	15%	22%	1,093	198	250	18%	23%	32.0%	$266	$27
		D	7.43	2.33	3.14	31%	42%	0.623	0.100	0.235	16%	38%	11,737	1518	2284	13%	19%	48.7%	$1,423	$144
	HHD	D	44.93	5.03	10.40	11%	23%	1.657	0.063	0.222	4%	13%	30,340	1255	2964	4%	10%	32.5%	$1,164	$305
	Total		*76.15*	*15.48*	*23.22*	*20%*	*30%*	*2.596*	*0.230*	*0.561*	*9%*	*22%*	*53,690*	*5177*	*8229*	*10%*	*15%*		*$4,944*	*$688*
Battery Electric	LHD1	G	11.84	5.34	5.34	45%	45%	0.158	0.041	0.047	26%	30%	7,101	1672	1911	24%	27%	34.7%	$1,631	$348
		D	4.54	2.00	2.00	44%	44%	0.060	0.020	0.022	33%	36%	1,167	265	304	23%	26%	34.0%	$374	$80
	LHD2	G	2.27	1.11	1.11	49%	49%	0.032	0.009	0.010	28%	32%	1,483	378	432	25%	29%	37.6%	$430	$79
		D	3.10	1.49	1.49	48%	48%	0.040	0.014	0.016	36%	40%	768	189	217	25%	28%	36.4%	$312	$57
	MHD	G	2.06	0.67	0.67	32%	32%	0.026	0.005	0.006	19%	22%	1,093	184	211	17%	19%	21.8%	$191	$55
		D	7.43	2.81	2.81	38%	38%	0.623	0.212	0.231	34%	37%	11,737	2287	2624	19%	22%	33.3%	$1,028	$295
	HHD	D	44.93	4.81	4.81	11%	11%	1.657	0.136	0.150	8%	9%	30,340	1670	1916	6%	6%	9.1%	$445	$257
	Total		*76.15*	*18.22*	*18.22*	*24%*	*24%*	*2.596*	*0.437*	*0.482*	*17%*	*19%*	*53,690*	*6645*	*7615*	*12%*	*14%*		*$4,410*	*$1,172*

Exhibit 3-20. Advanced Truck Technology Scenario Benefits in 2035

			NOx (tpd)					PM2.5 (tpd)					GHGs (tpd)					Penetration	Cost (Millions)	
			SCAB Baseline	Reduction		% of Baseline		SCAB Baseline	Reduction		% of Baseline		SCAB Baseline	Reduction		% of Baseline				
Tech	Class	Fuel		low	high	low	high		low	high	low	high		low	high	low	high		Vehicles	Infrast.
Natural Gas	LHD1	G	11.03	2.02	3.03	18%	27%	0.187	0.000	0.000	0%	0%	8,584	1649	2983	19%	35%	86.7%	$2,892	$117
		D	3.04	0.55	0.82	18%	27%	0.060	0.004	0.011	6%	19%	1,352	244	452	18%	33%	85.1%	$545	$16
	LHD2	G	2.07	0.39	0.59	19%	28%	0.038	0.000	0.000	0%	0%	1,813	361	654	20%	36%	91.7%	$532	$26
		D	1.88	0.35	0.53	19%	28%	0.038	0.002	0.007	6%	19%	898	167	310	19%	35%	88.8%	$379	$11
	MHD	G	1.42	0.35	0.48	24%	34%	0.032	0.000	0.000	0%	0%	1,327	271	490	20%	37%	89.7%	$613	$19
		D	9.23	2.28	3.19	25%	35%	0.823	0.075	0.226	9%	27%	12,609	2493	4612	20%	37%	97.0%	$2,532	$174
	HHD	D	59.32	20.47	29.25	35%	49%	2.164	0.178	0.535	8%	25%	36,926	7283	13474	20%	36%	96.6%	$2,285	$519
	Total		*87.99*	*26.41*	*37.89*	*30%*	*43%*	*3.342*	*0.260*	*0.779*	*8%*	*23%*	*63,509*	*12468*	*22974*	*20%*	*36%*		*$9,778*	*$883*
Hybrid Electric	LHD1	G	11.03	1.12	2.13	10%	19%	0.187	0.020	0.029	11%	16%	8,584	1570	2748	18%	32%	86.7%	$1,701	$0
		D	3.04	1.15	1.70	38%	56%	0.060	0.009	0.017	15%	28%	1,352	244	427	18%	32%	85.1%	$321	$0
	LHD2	G	2.07	0.22	0.41	11%	20%	0.038	0.004	0.006	11%	16%	1,813	344	602	19%	33%	91.7%	$313	$0
		D	1.88	0.73	1.09	39%	58%	0.038	0.006	0.011	16%	29%	898	167	293	19%	33%	88.8%	$223	$0
	MHD	G	1.42	0.11	0.24	7%	17%	0.032	0.004	0.006	12%	18%	1,327	258	451	19%	34%	89.7%	$511	$0
		D	9.23	3.24	5.07	35%	55%	0.823	0.069	0.220	8%	27%	12,609	2493	4362	20%	35%	97.0%	$2,110	$0
	HHD	D	59.32	17.77	23.57	30%	40%	2.164	0.067	0.420	3%	19%	36,926	1805	7219	5%	20%	93.9%	$2,778	$0
	Total		*87.99*	*24.33*	*34.20*	*28%*	*39%*	*3.342*	*0.179*	*0.708*	*5%*	*21%*	*63,509*	*6881*	*16103*	*11%*	*25%*		*$7,957*	*$0*
Plug-In Hybrid	LHD1	G	11.03	6.52	7.47	59%	68%	0.187	0.039	0.052	21%	28%	8,584	3103	3835	36%	45%	86.3%	$2,283	$151
		D	3.04	1.93	2.45	64%	81%	0.060	0.016	0.030	26%	49%	1,352	477	591	35%	44%	85.0%	$459	$34
	LHD2	G	2.07	1.27	1.46	62%	71%	0.038	0.008	0.011	21%	29%	1,813	682	843	38%	46%	89.9%	$630	$34
		D	1.88	1.25	1.58	66%	84%	0.038	0.010	0.020	27%	51%	898	331	410	37%	46%	88.8%	$452	$24
	MHD	G	1.42	0.56	0.69	39%	48%	0.032	0.006	0.008	18%	26%	1,327	457	588	34%	44%	91.2%	$559	$48
		D	9.23	4.82	6.50	52%	70%	0.823	0.203	0.480	25%	58%	12,609	3182	4483	25%	36%	90.8%	$2,219	$189
	HHD	D	59.32	15.21	31.45	26%	53%	2.164	0.156	0.552	7%	26%	36,926	3884	8588	11%	23%	91.3%	$2,948	$513
	Total		*87.99*	*31.57*	*51.60*	*36%*	*59%*	*3.342*	*0.438*	*1.153*	*13%*	*34%*	*63,509*	*12117*	*19339*	*19%*	*30%*		*$9,551*	*$993*
Battery Electric	LHD1	G	11.03	9.35	9.35	85%	85%	0.187	0.051	0.058	27%	31%	8,584	3797	4341	44%	51%	77.7%	$3,065	$295
		D	3.04	2.54	2.54	83%	83%	0.060	0.025	0.028	42%	47%	1,352	581	666	43%	49%	75.9%	$626	$67
	LHD2	G	2.07	1.83	1.83	88%	88%	0.038	0.011	0.012	28%	32%	1,813	834	954	46%	53%	82.2%	$701	$66
		D	1.88	1.64	1.64	87%	87%	0.038	0.017	0.019	44%	49%	898	403	462	45%	52%	80.3%	$504	$47
	MHD	G	1.42	1.24	1.24	88%	88%	0.032	0.010	0.011	31%	35%	1,327	606	693	46%	52%	73.0%	$520	$88
		D	9.23	7.97	7.97	86%	86%	0.823	0.592	0.644	72%	78%	12,609	5606	6432	44%	51%	75.0%	$2,038	$346
	HHD	D	59.32	49.93	49.93	84%	84%	2.164	1.162	1.283	54%	59%	36,926	15997	18353	43%	50%	68.7%	$3,175	$884
	Total		*87.99*	*74.50*	*74.50*	*85%*	*85%*	*3.342*	*1.867*	*2.056*	*56%*	*62%*	*63,509*	*27824*	*31901*	*44%*	*50%*		*$10,629*	*$1,794*

Exhibit 3-21 summarizes the emission reductions and associated incremental vehicle costs for each of the four major technology options. This summary highlights the following points:

- With the exception of battery electric trucks, advanced technology trucks are generally more effective at reducing NOx than PM.
- In 2023, advanced technology trucks could potentially reduce HDV NOx emissions in the range of 20-37% and HDV PM2.5 emissions in the range of 6-26%.
- In 2023, the emissions benefits of the natural gas, hybrid, and plug-in hybrid truck scenarios are similar.
- Because they are not expected to be commercially available on a large scale for at least five to ten years, plug-in hybrid and battery electric trucks offer relatively modest potential emissions benefits in 2023 as compared to 2035.
- In 2035, battery electric trucks offer the potential for significantly greater emission reductions than the other three technology options.

Exhibit 3-21. Summary of Benefits and Costs of Advanced Truck Technology Scenarios for 2023 and 2035, SCAB

	NOx					PM2.5					GHGs						
	SCAB Baseline (tpd)	Reduction (tpd)		% of Baseline		SCAB Baseline (tpd)	Reduction (tpd)		% of Baseline		SCAB Baseline (tpd)	Reduction (tpd)		% of Baseline		Cost (Millions)	
Technology		low	high	low	high		low	high	Low	high		low	high	low	high	Vehicle	Infrast.
2023																	
Natural Gas	76.2	19.8	28.5	26%	37%	2.60	0.19	0.66	7%	26%	53,690	9,546	17,605	18%	33%	$7,165	$653
Hybrid Electric		17.4	24.7	23%	32%		0.15	0.58	6%	22%		5,058	11,742	9%	22%	$7,161	$0
Plug-In Hybrid		15.5	23.2	20%	30%		0.23	0.56	9%	22%		5,177	8,229	10%	15%	$4,944	$688
Battery Electric		18.2	18.2	24%	24%		0.44	0.48	17%	19%		6,645	7,615	12%	14%	$4,410	$1,172
2035																	
Natural Gas	88.0	26.4	37.9	30%	43%	3.34	0.26	0.78	8%	23%	63,509	12,468	22,974	20%	36%	$9,778	$883
Hybrid Electric		24.3	34.2	28%	39%		0.18	0.71	5%	21%		6,881	16,103	11%	25%	$7,957	$0
Plug-In Hybrid		31.6	51.6	36%	59%		0.44	1.15	13%	34%		12,117	19,339	19%	30%	$9,551	$993
Battery Electric		74.5	74.5	85%	85%		1.87	2.06	56%	62%		27,824	31,901	44%	50%	$10,629	$1,794

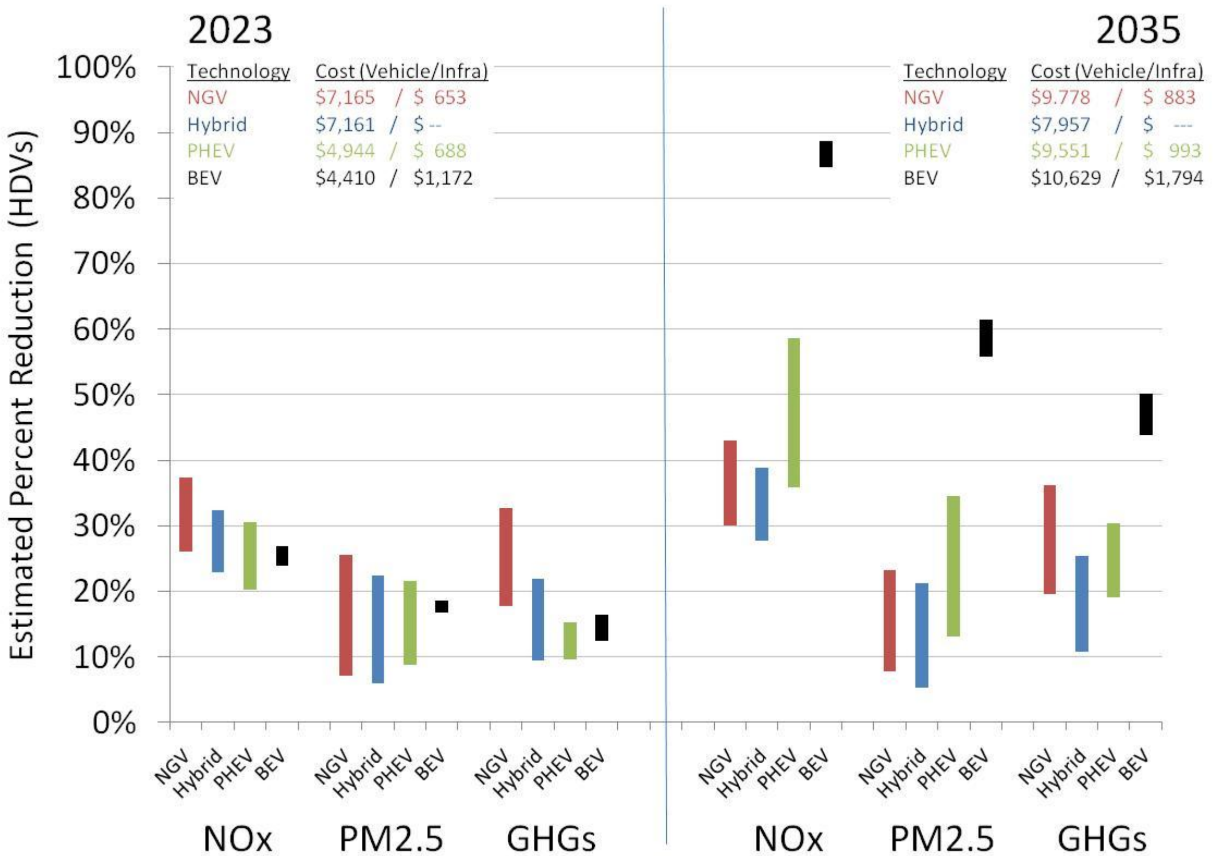
Exhibit 3-22 shows a similar summary of benefits and costs for the entire SCAG region.

Exhibit 3-22. Summary of Benefits and Costs of Advanced Truck Technology Scenarios for 2023 and 2035, SCAG Region

	NOx					PM2.5					GHGs						
		Reduction (tpd)		% of Baseline			Reduction (tpd)		% of Baseline			Reduction (tpd)		% of Baseline		Cost (Millions)	
Technology	Baseline (tpd)	low	high	low	high	Baseline (tpd)	low	high	Low	high	Baseline (tpd)	low	high	low	high	Vehicle	Infrast.
2023																	
Natural Gas	118.0	32.7	46.8	26%	37%	4.14	0.30	1.09	7%	26%	83,515	15,059	27,793	18%	33%	$9,809	$1,082
Hybrid Electric		27.8	38.8	23%	32%		0.21	0.90	6%	22%		6,732	17,173	9%	22%	$10,030	$0
Plug-In Hybrid		21.4	33.9	20%	30%		0.31	0.80	9%	22%		6,885	11,617	10%	15%	$6,716	$1,050
Battery Electric		24.4	24.4	24%	24%		0.59	0.66	17%	19%		8,864	10,159	12%	14%	$5,541	$1,580
2035																	
Natural Gas	147.7	46.3	66.4	30%	43%	5.55	0.44	1.32	8%	23%	102,914	20,230	37,317	20%	36%	$13,441	$1,490
Hybrid Electric		41.8	57.7	28%	39%		0.26	1.14	5%	21%		9,373	24,357	11%	25%	$11,732	$0
Plug-In Hybrid		48.4	84.1	36%	59%		0.63	1.76	13%	34%		17,118	29,223	19%	30%	$13,777	$1,614
Battery Electric		124.8	124.8	85%	85%		3.06	3.37	56%	62%		44,942	51,538	44%	50%	$15,268	$2,878

Exhibit 3-23 summarizes this information in graphical format.

Exhibit 3-23. Summary of Benefits and Costs of Advanced Truck Technology Scenarios for 2023 and 2035, SCAB



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4. Railroad Emissions Baseline

4.1. Introduction

The SCAG region is served by two Class I railroads, Union Pacific (UP) and Burlington Northern Santa Fe (BNSF), which together account for the vast majority of railroad activity and emissions in the region. Several small railroads provide local freight service, including Pacific Harbor Lines (PHL).

Locomotives are often categorized based on size (installed horsepower) and type of use. For this report, we consider three locomotive categories for purpose of identifying emission reduction options:

- Class I Line Haul Locomotives are generally newer (built 1995 and later) and high power (greater than 4,000 hp) locomotives that typically operate over long distances and travel through many states. On a typical trip, such as between Chicago and Los Angeles, an interstate line haul locomotive may operate in California for only 10 to 20 percent of the trip. This category also includes some smaller (3,000 – 4,000 hp) locomotives operated by the Class I railroads that tend to remain within Southern California. ARB defines these intrastate locomotives as medium horsepower units that spend at least 90 percent of operating time, fuel, and locomotive miles within the state. Because intrastate locomotives are significantly older than interstate line-haul locomotives, this distinction becomes relevant when evaluating the benefits and costs of emission control strategies. [30]
- Class II/III Locomotives are utilized by local and regional railroads for operation within Southern California. The largest Class II operator, Pacific Harbor Lines, operates 23 locomotives that provide service between on-dock rail terminals at the ports of Los Angeles and Long Beach and nearby railyards and the Alameda Corridor.
- Switch (Yard) Locomotives are typically used to push railcars together to form trains within railyards, but can also be used to power local and regional service. For the purpose of this analysis, this category includes switchers owned by interstate and regional railroads.

Passenger train locomotives operated by Metrolink and Amtrak also contribute to railroad emissions. Although not involved in goods movement, emissions from passenger locomotives are often reported together with freight locomotives in regional emission inventories and air quality planning documents. Therefore, we include passenger locomotive emissions in the baseline estimates in this report, although do not present strategies for reducing passenger locomotive emissions. Passenger locomotives typically are 3,000 hp to 3,600 hp.

Because most Class I locomotives travel nationwide, it is not possible to define a "Class I fleet" within the SCAB or SCAG region. In actuality, a large pool of locomotives may operate in or pass through the SCAG region over the course of a year, and at any given time only a fraction are present in the region.

4.2. Key Locomotive Regulations

Since 1998, the U.S. EPA and ARB have implemented a number of regulations and programs to control locomotive emissions, including emissions standards for new and remanufactured locomotive engines, fuel sulfur content regulations, and limits on locomotive idling. This section briefly reviews key federal and state regulations in this sector.

[30] Air Resources Board, *Technical Options to Achieve Additional Emissions and Risk Reductions from California Locomotives and Railyards*, August 2009.

U.S. EPA Regulations

Locomotive Engine Standards

In 1998, and amended in 2008, EPA created several tier standards for locomotive engines. The standards apply to all newly manufactured and remanufactured locomotives used in line-haul, passenger, and switcher service within the United States. An exception applies to locomotives originally manufactured before 1973, which are not subject to emissions standards. For new locomotives, the Tier 2 standards took effect beginning in 2005. Tier 3 and Tier 4 standards take effect beginning in 2012 and 2015, respectively. The reduction required under Tier 4 emission standards are akin to the 2007/2010 heavy-duty truck standards and will likely necessitate the use of aftertreatment technologies (e.g., diesel particulate filters and selective catalytic reduction) by locomotive manufacturers.

Control of Emissions from Idling Locomotives

The 2008 EPA rulemaking added new requirements to further reduce emissions from idling locomotives by requiring technology that reduces the amount of time a locomotive spends idling and applying tighter emission standards to new locomotives generally.[31] EPA is requiring that all newly manufactured and nearly all remanufactured locomotives be equipped with idle reduction technology that will automatically shut locomotives down if they are left idling unnecessarily. While such devices cannot eliminate all idling, they can reduce most unnecessary idling.

NRLM Fuel Sulfur Rule

EPA adopted standards to control the amount of sulfur present in non-road, locomotive, and marine (NRLM) diesel fuel.[32] Reducing sulfur content directly reduces particulate emissions and also enables the use of exhaust aftertreatment devices that can be fouled by high sulfur levels. Beginning June 1, 2007, refiners are required to produce NRLM diesel fuel with a maximum sulfur content of 500 ppm ("low sulfur diesel"). Beginning June 1, 2012, the sulfur content is reduced for locomotive diesel fuel limited to a maximum of 15 ppm ("ultra low sulfur diesel"). As described below, ARB regulations have imposed a more aggressive schedule to lower sulfur content for locomotive fuel sold in California.

ARB Regulations

South Coast Memorandum of Understanding (MOU)

As part of California's 1994 State Implementation Plan, ARB developed a MOU with UP and BNSF that was signed in July 1998. The MOU includes provisions for early introduction of clean units, with requirements for a locomotive fleet average in the South Coast Air Basin equivalent to EPA's Tier 2 locomotive standard by 2010. The railroads have complied with this requirement.

Requirements for Intrastate Locomotive Fuel Use

In 2004, ARB approved requirements for fuel used in intrastate locomotives that accelerate the implementation of EPA's ultra low sulfur diesel requirements. Beginning January 1, 2007, diesel fuel sold for use in intrastate locomotives operating in California was required to meet the specifications of CARB diesel fuel (15 ppm sulfur). The regulation does not apply to locomotives entering California in interstate service.

[31] See http://www.epa.gov/otaq/regs/nonroad/locomotv/420f08014.htm

[32] See http://www.epa.gov/nonroad-diesel/2004fr/420r04007.pdf

Statewide Rail Yard Agreement to Reduce Diesel PM at California Rail Yards

ARB's 2005 agreement with UP and BNSF requires the railroads to significantly reduce diesel emissions in and around railyards in California.[33] Among the most important elements of the agreement are: 1) a statewide idling-reduction program, 2) health risk assessments for all major rail yards, 3) community and air district involvement in the preparation of risk assessments, enforcement of Agreement provisions, and the evaluation and development of measures to further reduce impacts on local communities. The Agreement will also: 1) maximize the use of state and federal low sulfur diesel in locomotives fueled in California, 2) establish a statewide visible emissions reduction and repair program, 3) provide a detailed evaluation of advanced control measures, and 4) includes an assessment of remote sensing technology to identify high-emitting locomotives.

2010 Commitments to Further Reduce Diesel PM Emissions at Four High Priority Railyards

In 2010, ARB proposed further binding voluntary commitments to reduce diesel PM emissions at four railyards: BNSF San Bernardino, BNSF Hobart, UP Commerce, and UP ICTF/Dolores. The agreement would set a maximum level of emissions starting in 2011 that could not be exceeded, regardless of the level of growth that occurs at the railyards. Compared to the 2005 baseline, this agreement would require a 65-75% reduction in diesel PM emissions by 2015 and an 85% reduction by 2020. ARB is currently considering revisions to the 2010 commitments.

4.3. Locomotive Emissions Standards and Rates

As part of its regulatory program for the locomotive sector, EPA defines emission standards for locomotive engines, with more stringent standards applied to newer model years. The agency currently defines five primary emission tiers, based on the year of original locomotive engine manufacture. The Tier 0 emission standards apply to locomotives and engines either originally manufactured from 1973 through 2001 or remanufactured in that time period. Tier 1 standards apply to original model years between 2002 through 2004. Tier 2 standards apply to original model years of 2005 and later. Tier 3 locomotives will be introduced starting with the 2012 model year, and Tier 4 will be required starting with model year 2015. In addition, when in-use locomotives are overhauled and their engines rebuilt, they must meet more aggressive emission standards. Units in Tiers 0, 1, and 2 must be rebuilt to the standards of Tiers 0+, 1+, and 2+, respectively.

EPA has estimated emission factors that reflect expected emission rates, accounting for manufacturer compliance margins.[34] Exhibits 4-1 and 4-2 summarize the emission standards and factors for line haul and switch locomotives, respectively.

[33] More information on ARB's locomotive emission reduction program can be found at: http://www.arb.ca.gov/msprog/offroad/loco/loco.htm

[34] US EPA, "Technical Highlights: Emission Factors for Locomotives". EPA-420-F-09-025. April 2009.

Exhibit 4-1. EPA emission standards and in-use emission factors for line-haul locomotives (g/hp-hr)

Tier	Year of Manufacture	EPA Standard		In-Use Emission Factors	
		NOx	PM	NOx	PM-10
Uncontrolled	Pre-1973	13.0	0.32	13	0.32
Tier 0	1973 – 2001	9.5	0.60	8.6	0.32
Tier 0+	2008 / 2010	7.4	0.22	7.2	0.20
Tier 1	2002 – 2004	7.4	0.45	6.7	0.32
Tier 1+	2008 / 2010	7.4	0.22	6.7	0.20
Tier 2	2005	5.5	0.20	4.95	0.18
Tier 2+	2008 / 2013	5.5	0.10	4.95	0.08
Tier 3	2012 – 2014	5.5	0.10	4.95	0.08
Tier 4	2015 / 2017	1.3	0.03	1.0	0.015

Source: US EPA, "Technical Highlights: Emission Factors for Locomotives". EPA-420-F-09-025. April 2009.

Exhibit 4-2. EPA emission standards and in-use emission factors for switch locomotives (g/hp-hr)

Tier	Year of Manufacture	EPA Standard		In-Use Emission Factors	
		NOx	PM	NOx	PM-10
Uncontrolled	Pre-1973	17.4	0.44	17.4	0.44
Tier 0	1973 - 2001	14	0.72	12.6	0.44
Tier 0+	2008 / 2010	11.8	0.26	10.6	0.23
Tier 1	2002 - 2004	11	0.54	9.9	0.43
Tier 1+	2008 / 2010	11	0.26	9.9	0.23
Tier 2	2005	8.1	0.24	7.3	0.19
Tier 2+	2008 / 2013	8.1	0.13	7.3	0.11
Tier 3	2012 - 2014	5	0.1	4.5	0.08
Tier 4	2015 / 2017	1.3	0.03	1	0.015
Tier 3 GenSet	2006	3	0.15	3.0	0.15
Tier 4 GenSet	2011-2014	0.3	0.01	0.3	0.01

Source: US EPA, "Technical Highlights: Emission Factors for Locomotives". EPA-420-F-09-025. April 2009.

4.4. Baseline Locomotive Emissions to 2035

Since the 1990s, the locomotive emission inventories used for air quality planning in California have been based on a 1992 study prepared for ARB, *Report on Locomotive Emission Inventory: Locomotive Emissions by County*.[35] This original 1992 county-level emission inventory has been updated over the years to account for activity growth and changes in locomotive fleet characteristics, but has not been verified against any primary data source since the original study. ARB has prepared projections of future year emissions by applying growth factors and the anticipated effects of emissions standards. The agency

[35] Booz Allen and Hamilton, *Report on Locomotive Emission Inventory: Locomotive Emissions by County*, California Air Resources Board, 1992.

is currently in the process of developing an entirely new locomotive emission inventory, using detailed information on the locomotive fleet operating in California as provided by the railroads. This updated inventory is expected to be available in late 2011 or 2012.

In order to evaluate the effectiveness of locomotive emission reduction options, ICF has developed an estimate of baseline locomotive emissions in the South Coast Air Basin through 2035. This estimate is based on information from several sources, including: state- and national-level estimates by ARB and EPA, SCAB-region train counts and projections,[36] and SCAG stakeholder input on ICF's assumptions.

Methodology

We estimated locomotive population, activity, and emissions separately for four locomotive types: Class I interstate line haul, Class II/III intrastate line haul, switch, and passenger. The baseline locomotive fleet was determined for each group based on several inputs:

- The Class I baseline for 2010 was provided by the railroads through California Environmental Associates, specifying an average of 660 line-hauls operating within SCAB on a given day. Of these, two-thirds were reported to be Tier 2, with the remainder split between Tier 0 and Tier 1.[37] The geographical boundary for the locomotive fleet projections is the South Coast Air Basin.
- The Class II/III baseline for 2010 is based on ARB and ICF estimates of the regional rail, most notably Pacific Harbor Lines. PHL currently operates 23 Tier 2 locomotives, and has announced plans to upgrade to Tier 3 units in the near future.
- The baseline switcher locomotive fleet is based on the fleet size and emissions tier mix reported by ARB.[38]
- The current passenger locomotive fleet is based on data reported by Metrolink, supplemented with ICF estimates of the Amtrak fleet.

Using this baseline of present-year inventory, the future year fleet was estimated using a combination of growth factors and projections of changes in fleet mix. The key variable in future year calculations is the assumed annual growth factor. EPA assumed a nationwide average annual growth rate of 1.38% for the Class I line haul locomotive fleet in its 2008 rulemaking. However, this growth is not indicative of likely growth within SCAB, which is uniquely positioned to accommodate growing freight levels from the ports. Analysis performed for SCAG as part of the Regional Goods Movement Study implies that SCAB locomotive-miles will grow at an average annual rate of 3.72%. Since this value is based on local railroad activity and port growth projections, it was chosen as the most applicable growth rate.

The annual growth rate of 3.72% represents the change in locomotive activity (measured in locomotive-miles) between 2010 and 2035. The growth rate is based on analysis for SCAG that developed forecasts of freight train volumes in each segment of the rail system in the region.[39] The train volume on each segment was multiplied by the length of that segment to calculate train miles for each train type (e.g., 8,000 foot double stack intermodal). Using assumptions for the number of locomotives required to move each train type, a forecast was developed for locomotive miles. Because the projections were made

[36] DRAFT SCAG Goods Movement Study Rail Grade Crossings Impact Evaluation, Cambridge Systematics, 2011.

[37] California Environmental Associates, "Preliminary Comments on Baseline Emissions Estimates and tier 4 Acceleration Assumptions", May 17, 2011.

[38] Air Resources Board, *Technical Options to Achieve Additional Emissions and Risk Reductions from California Locomotives and Railyards*, August 2009.

[39] DRAFT SCAG Goods Movement Study Rail Grade Crossings Impact Evaluation, Cambridge Systematics, 2011

holistically across the rail system, granular details such as flat vs. non-flat segments were not directly included. The growth rate of SCAB locomotive miles is assumed to be a reasonable proxy for the growth rate of SCAB locomotive population and fuel consumption.

The growth rates for the population of other types of locomotives (Switcher engines, Class II/III MHP locomotives, and passenger locomotives) is likely to be lower than that of line-haul locomotives, although there is little basis for developing such a growth rate specific to Southern California. The railroad industry has suggested that PHL switching grows at a rate no more than half that of Class I traffic.[40] We assume the growth rate for both switchers and MHP locomotives will be one-half of the line haul growth rate. For passenger locomotives, we use the EPA nationwide growth factor for passenger locomotives, 0.8% annually.[41]

This approach to the growth in locomotive activity is consistent with projections used to analyze mainline electrification options. It has been noted by SCAG stakeholders that actual locomotive purchase rates vary considerably from year to year in response to business needs. In fact, the nationwide switcher fleet has declined in the last 12 years. Further, locomotive activity would not scale linearly with increased freight traffic, as improvements in operational efficiency can reduce the number of locomotives needed to move a given amount of freight. However, in the absence of other Southern California-specific locomotive demand forecasts, the SCAB locomotive forecasts form the best basis for calculating activity for the purposes of this study.

While these results provide a growth factor for total fleet size in future years, there are no projections of expected fleet mix within SCAB, i.e., the percentage of locomotives within each emissions tier. While the local current-year fleet mix differs from nationwide average fleet mix due to the Tier 2 MOU, we assume that in the absence of additional regulation, agreements, or incentive programs, the SCAB fleet mix in future years will converge with nationwide averages as the nationwide fleet becomes cleaner. For this reason, in future years we apply the fleet mix from EPA nationwide projections.

We assume that all new interstate line haul locomotives, passenger locomotives, and switch locomotives purchased will meet Tier 3 standards in 2012-2014 and Tier 4 standards beginning in 2015, consistent with EPA's estimate. In addition, consistent with EPA's estimates, we assume that all uncontrolled (pre-Tier 0) locomotives are retired by 2019 and all Tier 2 locomotives are rebuilt to Tier 2+ standard by 2019.

To estimate emissions, we first estimate fuel consumption using the following assumptions of average annual fuel use per locomotive in the SCAB:[42]

- Class I line haul – 50,000 gallons
- Class II/III – 25,000 gallons
- Passenger – 100,000 gallons[43]
- Switcher – 25,000 gallons for single engine switchers,

[40] California Environmental Associates, Memo to Annie Nam, Southern California Association of Governments. October 14, 2011.

[41] US EPA, "Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder", EPA420-R-08-001a, May 2008.

[42] Fuel consumption figures provided by ARB, unless otherwise noted. Air Resources Board, *Technical Options to Achieve Additional Emissions and Risk Reductions from California Locomotives and Railyards*, August 2009.

[43] Note that Metrolink locomotives consumed 117,000 gallons per locomotive on average in 2009, according to the National Transit Database. This value is consistent with ARB and EPA assumptions regarding passenger locomotives.

To calculate brake horsepower hours, we assumed brake-specific fuel consumption (in bhp/gallon) of 20.8 for line haul and passenger locomotives and 15.2 for switchers, consistent with EPA guidance.[44] Lastly, we apply the emission factors shown above to estimate emission of PM and NOx. To estimate CO2 emissions, 22.2 pounds of CO2 per gallon of diesel.

Results

Exhibit 4-3 shows the projected number of Class I line haul, Class II/III, and passenger locomotives operating in the SCAB through 2035.

Exhibit 4-3. Projected baseline line haul and passenger locomotive fleet operating in SCAB

Year	Type	Pre-0	Tier 0	Tier 1	Tier 2	Tier 2+	Tier 3	Tier 4	Total
2010	Class I line haul	0	110	110	440	0	0	0	660
	Class II/III	0	12	0	16	0	6	1	35
	Passenger	0	32	0	30	0	0	0	62
	Total	0	154	110	486	0	6	1	757
2023	Class I line haul	0	110	92	0	401	102	357	1,061
	Class II/III	0	0	0	0	12	31	1	44
	Passenger	0	0	0	15	15	15	24	69
	Total	0	110	92	15	428	148	382	1,175
2035	Class I line haul	0	57	49	0	187	119	1,234	1,646
	Class II/III	0	0	0	0	12	9	34	56
	Passenger	0	0	0	0	30	15	31	76
	Total	0	57	49	0	229	143	1,299	1,777

Exhibit 4-4 shows the projected number of switch locomotives operating in the SCAB through 2035.

Exhibit 4-4. Projected baseline switch locomotive fleet operating in SCAB

Year	Pre-0	Tier 0	Tier 0+	Tier 3 Loco	Tier 4 Loco	Tier 3 GenSet	Tier 4 GenSet	ULESL	Total
2010	34	29	0	0	0	61	0	15	139
2023	0	0	29	10	37	71	37	0	183
2035	0	0	0	10	74	71	74	0	229

Exhibit 4-5 shows graphically the how the population of line haul locomotives (Class I & Class II/III) is expected to change over time.

[44] U.S. EPA, Emission Factors for Locomotives, available at: http://www.epa.gov/otaq/regs/nonroad/locomotv/420f09025.pdf

Exhibit 4-5. Projected baseline freight line haul (Class I & Class II/III) locomotive fleet operating in SCAB

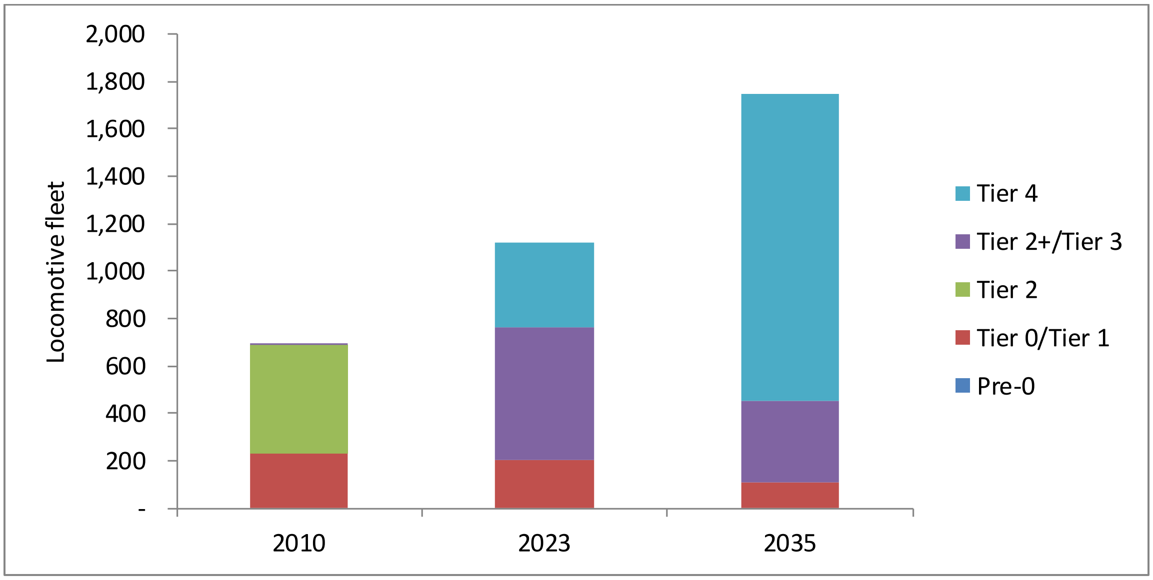


Exhibit 4-6 shows the estimated baseline NOx, PM, and CO2 emissions by locomotive type.

Exhibit 4-6. Projected baseline locomotive emissions in South Coast Air Basin (tons per day)

	NOx			PM2.5			CO2		
Type	2010	2023	2035	2010	2023	2035	2010	2023	2035
Line-haul	12.1	13.4	10.9	0.47	0.27	0.20	1,004	1,614	2,503
Switcher	1.4	0.7	0.4	0.04	0.02	0.01	94	123	152
Class II-III	0.3	0.3	0.2	0.01	0.01	0.00	27	34	42
Passenger	2.7	1.5	1.6	0.10	0.03	0.03	189	196	209
Total	16.5	15.9	13.1	0.62	0.33	0.24	1,313	1,967	2,906

5. Railroad Technological Strategies

5.1. Emission Reduction Strategies – Line-haul Locomotives

This section discusses the emissions benefits and costs of three strategies for reducing line-haul locomotive emissions:

- Accelerate deployment of Tier 4 line haul locomotives by 2023
- Accelerate deployment of Tier 4 line haul locomotives by 2035
- Implement technologies that propel locomotives without diesel, such as electrification

Strategy 1: Accelerate deployment of Tier 4 line haul locomotives by 2023

Beginning in 2015, new locomotives will meet Tier 4 emissions standards, and the percent of Tier 4 units in the railroads' fleets will grow over time as more new locomotives are purchased and older locomotives are retired. By 2023, under the baseline scenario, we estimate that 34% of the nationwide Class I line haul fleet will be Tier 4, based on the U.S. EPA's projections used in the 2008 rulemaking. The strategy described in this section would accelerate the introduction of Tier 4 line haul locomotives into the Class I fleets that serve Southern California.

This strategy could be implemented using government incentives, a new MOU between ARB and the railroads, or some combination of the two.

- If available, government incentives could be used to subsidize the purchase of new Tier 4 locomotives for the railroads. By accepting public funds, the railroads would agree to dedicate the subsidized locomotives to Southern California interstate service, supplementing Tier 4 units the railroads would already be using for Southern California. The railroads would necessarily shift Tier 2+ or Tier 3 line haul locomotives to other U.S. service areas or retire them. The availability of government funds for this purpose is uncertain.
- Under a new MOU, the railroads would agree to concentrate their Tier 4 locomotives to Southern California interstate service to achieve a Tier 4 fleet average, similar to the Tier 2 fleet average agreement signed in 1998. This would likely require the railroads to shift Tier 4 units from other U.S. service areas.

The benefits and costs of these policy mechanisms are not analyzed in this report.

While currently there are no technologies in the marketplace that exceed Tier 4 standards, if technologies are available in 2023, this could be used to offset some remaining Tier 2+ or Tier 3 engines. If no such technologies exist, then a Tier 4 fleet average would effectively be composed of 100% Tier 4 line haul units. Implementation of any MOU would depend on negotiations between the railroads and state regulatory agencies. At this time, the ARB has not committed to implementation of such an MOU. Such an agreement is outside the scope of authority of SCAG.

As discussed above, the SCAB does not have a captive line-haul locomotive fleet. Instead, line-haul units travel throughout the western U.S., and the total number of locomotives that enter the SCAB in a year is significantly larger than the number of locomotives present in any given day. Because of this, the railroads would need to operate a fleet of Tier 4 locomotives larger than the 1,061 line haul units projected to be operating in the SCAB on a given day in 2023, as shown in Exhibit 4-3. While the total size of this fleet is unknown, the railroads have noted that a fleet up to four times the size of the daily

SCAB fleet would be needed, as reported by ARB.[45] If this figure is correct, and units cleaner than Tier 4 are not available, then UP and BNSF together would need to operate as many as 4,246 Tier 4 locomotives within the Air Basin by 2023. It is uncertain whether the two railroads would have that many Tier 4 locomotives in their fleet. In its 2008 rulemaking, EPA projected that 8,456 Class I Tier 4 line haul locomotives would be operating nationwide by 2023.[46] Given that UP and BNSF together own approximately 57% of the U.S. Class I locomotive fleet,[47] it is possible that they would have a Tier 4 line haul fleet large enough to achieve 100% Tier 4 in the SCAB by 2023. However, it would likely require the railroads to devote the majority of their newest units to Southern California routes and use older locomotives for other busy corridors, which may entail added operational costs in addition to the costs estimated in this analysis. These added operational costs are not quantified as part of this report.

The railroads have noted that achieving a Tier 4 line-haul fleet average emission rate by 2023 would be challenging, given the cost of the new locomotives and uncertainty about their performance. Historically, the development of new effective locomotive technology has taken an average of about seven to eight years, and in some cases more than a decade. In order to meet Tier 4 standards, significant improvements in both engine and aftertreatment technologies will be required (and demonstrated to be reliable). In contrast, Tier 2 standards were met with incremental improvements over existing technology.

While both railroads have implemented the Tier 2 MOU as of 2010, just five years following the introduction of Tier 2 locomotives, they have done- in part by deploying low emission switcher engines (primarily GenSets and hybrids) that exceed Tier 2 standards and thus offset remaining Tier 0 line haul units.

Emissions Impact

Implemented to its maximum extent (100% Tier 4 line haul), this strategy significantly reduces criteria pollutants by 2023, cutting NOx by 75% below the 2023 baseline and PM2.5 81% below the 2023 baseline. The large reductions are due to dramatic changes in fleet mix, with Tier 4 locomotives replacing Tier 0 – 3 units. These emission reductions are shown in Exhibit 5-1.

The benefits in year 2035 are smaller: NOx is reduced by 53% and PM2.5 by 62% as compared to the baseline. The emissions benefits are smaller in 2035 because the baseline fleet is significantly cleaner than the baseline fleet in 2023, due to fleet upgrades and retirements that would occur over time.

This strategy has no effect on CO2 emissions, since locomotive fuel economy is projected by EPA to be constant regardless of locomotive tier.

Exhibit 5-1. Maximum emission reductions from accelerated Tier 4 locomotive deployment by 2023 (tons per day)

	NOx			PM2.5			CO2		
Year	Line haul baseline	With Strategy	% Change	Line haul baseline	With Strategy	% Change	Line haul baseline	With Strategy	% Change
2010	12.1	12.1	0%	0.470	0.470	0%	1,004	1,004	0%
2023	13.4	3.3	-75%	0.270	0.050	-81%	1,614	1,614	0%
2035	10.9	5.2	-53%	0.202	0.078	-62%	2,503	2,503	0%

[45] Air Resources Board, *Technical Options to Achieve Additional Emissions and Risk Reductions from California Locomotives and Railyards*, August 2009.

[46] US EPA, "Regulatory Impact Analysis: Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less than 30 Liters Per Cylinder", EPA420-R-08-001a, May 2008.

[47] American Association of Railroads, "Railroad Facts 2010 Edition", November 2010.

Even if the full 100% deployment envisioned in this strategy were not fully achieved, any accelerated deployment of Tier 4 units will reduce emissions in the SCAB. For example, for every 100 Tier 4 line-haul locomotives that replace 100 Tier 2+ locomotives, the region would see a NOx reduction of 1.24 tpd and a PM2.5 reduction of 0.02 tpd. These reductions represent 10% and 8% of the baseline line haul emissions, respectively.

Costs

The cost of this strategy depends on how it is implemented. A new Tier 4 locomotive is assumed to cost $3 million, consistent with U.S. EPA assumptions. In order to achieve a 100% Tier 4 fleet, the railroads would need to operate 704 additional Tier 4 locomotives in the SCAB on a given day, on top of the 359 Tier 4 locomotives they are projected to operate under the baseline scenario. As noted above, as many as four times this number would be needed in the railroads' national fleet. Thus, as many as 2,817 additional Tier 4 locomotives would be needed.

If this strategy were implemented entirely using government incentive funds, and the railroads did not shift any locomotives among service areas, then the total cost would be $8.5 billion, distributed over the period 2015 to 2023. This should be considered an upper bound cost for this strategy.

The cost of this strategy would be considerably lower if the railroads are able to shift some Tier 4 units to Southern California service from other routes, or otherwise concentrate at least some of their Tier 4 fleet to Southern California. Costs could also be lower if new technologies become available that exceed the Tier 4 standards, thereby allowing the railroads to offset the emissions from some Tier 2+ and Tier 3 locomotives.

Strategy 2: Accelerate deployment of Tier 4 line haul locomotives by 2035

Similar to Strategy 1, this strategy would accelerate deployment of Tier 4 line haul locomotives in the SCAB, but would do so over a longer time period. The goal would be to achieve a Tier 4 fleet average for Class I line haul locomotives operating in the SCAB by 2035. As in the previous strategy, if no cleaner technology is developed beyond Tier 4 standards, then a Tier 4 fleet-average requirement would essentially become a Tier 4 mandate.

Under the baseline scenario, 75% of the Class I line haul fleet is projected to be Tier 4 by 2035. This strategy would accelerate the introduction of Tier 4 line haul locomotives to reach 100% Tier 4 by that year.

As with Strategy 1, this strategy could be implemented using government incentives, a new MOU between ARB and the railroads, or a combination of the two.

Emissions Impact

In order to meet 100% deployment in the interstate fleet by 2035, the railroads would need to operate an additional 412 Tier 4 units per day to supplement the 1,234 Tier 4 units projected to be in operation in that year under the baseline case. This strategy assumes that the accelerated deployment occurs at a steady pace, introducing 24 new units annually from 2016 to 2035. At this scheduled rate, 46% of the Class I line haul fleet within SCAB would be Tier 4 in 2023 (as compared to 34% in the baseline) and the entire line haul fleet is Tier 4 by 2035.

This strategy reduces NOx emissions by 53% and PM2.5 emission by 62% in year 2035, as compared to the total locomotive emission baseline. These 2035 reductions are equal to those under Strategy 1, since both achieve 100% Tier 4 in this year. Exhibit 5-2 shows the emission reductions that result from this strategy.

Assuming steady Tier 4 deployment, in 2023 this strategy would reduce NOx emissions by 30% and PM2.5 by 45%. These reductions are smaller than in the previous strategy, since a smaller portion of the fleet has been upgraded to Tier 4 in that year.

This strategy has no effect on CO2 emissions, since locomotive fuel economy is projected by EPA to be constant regardless of locomotive tier.

Exhibit 5-2. Maximum emission reductions from accelerated Tier 4 locomotive deployment by 2035 (tons per day)

	NOx			PM2.5			CO2		
Year	Line haul baseline	With Strategy	% Change	Line haul baseline	With Strategy	% Change	Line haul baseline	With Strategy	% Change
2010	12.1	12.1	0%	0.470	0.470	0%	1,004	1,004	0%
2023	13.4	9.4	-30%	0.270	0.149	-45%	1,614	1,614	0%
2035	10.9	5.2	-53%	0.202	0.078	-62%	2,503	2,503	0%

Costs

The costs of this strategy are considerably lower than Strategy 1, since only 412 new units are required under this strategy, compared to 704 in the previous strategy. Following the approach outlined above, with a $3 million per-unit cost and a nationwide multiplier of 4 to account for the impact on the nationwide fleet, the total cost of this strategy would be $4.9 billion. The costs would be incurred over 20 years starting in 2016, when Tier 4 locomotives are introduced.

A total cost of $4.9 billion should be considered an upper bound cost. Actual costs would be lower if the railroads are able to shift some Tier 4 units to Southern California service from other routes, or otherwise concentrate at least some of their Tier 4 fleet to Southern California. This is more likely than with Strategy 1, because the railroads would have far more Tier 4 locomotives in their national fleet by 2035. Costs could also be lower if new technologies become available that exceed the Tier 4 standards, thereby allowing the railroads to offset the emissions from some Tier 2+ and Tier 3 locomotives. Again, this is more likely than with Strategy 1 because the potential for technological advancement is greater over the longer time frame.

Strategy 3: Electrify the mainline railroad network by 2035

Railroad electrification would enable freight trains to be moved using electric rather than diesel locomotives, resulting in potentially large reductions in Southern California locomotive emissions. There are several technology options for electrification, including straight-electric locomotives with overhead catenary, dual-mode locomotives with overhead catenary, and a linear synchronous motor (LSM) system. Other technologies are also in development with the potential to replace diesel engines. More information about these options is presented in “Task 8.3, Analysis of Freight Rail Electrification in the SCAG Region” released as part of the SCAG Comprehensive Goods Movement Implementation Plan and Strategy, 2012 and produced by Cambridge Systematics. This report examined several geographic options and technologies for rail electrification, including operational concerns, potential costs, and emissions benefits.

The most encompassing route includes rail mainlines within SCAB and extending out beyond SCAB borders to Barstow and Indio. The strategy would include electrification of the Alameda Corridor, the UP Alhambra Sub, the UP LA Sub, and the BSNF Transcon lines out to Indio and Barstow. In addition, the

UP Santa Clara and UP Coast lines to the northwest of downtown Los Angeles would be electrified to Chatsworth and San Fernando. The analysis below focuses on Option III, shown in Figure 5-3. This option includes a total of 460 route miles. While this option expands outside of the South Coast Air Basin (SCAB), emissions changes are only calculated within SCAB boundaries. However, capital costs are estimated below for the complete length of Option III.

Exhibit 5-3. Potential Electrified Mainline Network (SCAG Region and SCAB)

Emissions Impact

The emission reductions due to this strategy are shown in Exhibit 5-4. Because an electrified network would not be operational until after 2023, the results shown in this exhibit are only quantified for year 2035.

For criteria pollutants such as PM and NOx, an electrification strategy would reduce locomotive emissions in two ways: first, by changing the power source to a cleaner-burning fuel, that is, switching from diesel fuel for a conventional locomotive to natural gas electrical generation; second, by shifting the location of the emissions to the power plant, which may or may not be located within the SCAB. While most electric generation plants produce criteria pollutants, this analysis is limited to the emissions produced locally within SCAB. This is consistent with several analysis criteria: first, it allows for a direct comparison to the pollutants from diesel locomotives operating within SCAB, and second, it focuses on emissions that affect local air quality. For this level of analysis, it is not feasible to determine the location of the power plant emissions for future years. Instead, we calculate the NOx and PM emissions assuming that 30% of the electrical generation for the electrified rail system occurs within the SCAB at natural gas power plants.[48]

For the sake of consistency, the estimation of CO2 emissions impacts also considers just the emissions produced within the SCAB, assuming 30% of the electrical generation for the electrified rail system occurs within the SCAB at natural gas power plants. However, it is important to recognize that, unlike criteria pollutants, greenhouse gases are a global pollutant and have the same impact on the local population regardless of the source of emission. In order to calculate GHGs, the analysis utilizes regional WECC-wide emission factors for 2020 assuming a 33% renewable electricity standard were in effect.[49]

Under the assumptions outlined above, the electrification strategy would reduce line-haul locomotive NOx by 96 percent and PM2.5 by 74 percent in 2035. The dramatic reduction in emissions is due to several factors. First, electric locomotives are twice as efficient as their diesel counterparts, requiring half as much fuel to perform the same amount of work. In this instance efficiency is measured specifically as locomotive efficiency, or the ratio of fuel (or electricity) consumed per brake-horsepower of motor output.[50] Second, natural gas combustion is cleaner than diesel combustion, especially in regards to PM, and third, emission control technology for natural gas power plants, including ammonia smokestack scrubbers, are highly efficient at removing NOx from the power plant waste stream.

This strategy also significantly reduces greenhouse gas emissions, cutting CO2 emissions in the SCAB by 80 percent compared to the line-haul baseline. Much of this reduction is attributable to the more-efficient nature of electric locomotives, while a smaller component of the reduction is the efficiency of the natural gas combustion cycle. In total, for locomotives traveling within the SCAB, the electrification strategy would reduce SCAB-generated CO2 emissions by 1,993 tons per day.

Exhibit 5-4. Emission reductions within SCAB from electrifying the mainline network by 2035 (tons per day)

	NOx			PM2.5			CO2		
Year	Line haul baseline	With Strategy	% Change	Line haul baseline	With Strategy	% Change	Line haul baseline	With Strategy	% Change
2035	10.9	0.41	-96%	0.20	0.051	-74%	2,503	510	-80%

[a] The NOx and PM emissions shown here are calculated as a scenario in which 30% of electricity used by the system is generated by natural gas power plants within SCAB.

Costs

The total cost of the electrification strategy includes outlays for capital expenses including construction costs of the upgraded electrified corridors and purchase costs of new rolling stock. All costs are presented in current-year dollars, excluding discounts for future year payments. The costs described here do not include operating costs associated with electric operation or land acquisition costs for new locomotive change-out points.

[48] Initial Statement Of Reasons Proposed Regulation To Implement The California Cap-And-Trade Program, Part I, Volume II, Appendix D, Supporting Documentation for the Environmental Analysis; October 28, 2010; Table D2-1.

[49] Initial Statement Of Reasons Proposed Regulation To Implement The California Cap-And-Trade Program, Part I, Volume II, Appendix D, Supporting Documentation for the Environmental Analysis; October 28, 2010; Table D1-5.

[50] Telephone conversation with Michael Latour, Siemens AG, July 15, 2011.

Significant investment will be required for any of the three technology alternatives, as shown in Exhibit 5-5. For the LSM option, a relatively high degree of uncertainty currently exists regarding costs, both in terms of LSM Helper Cars to help move the train and in terms of project costs. When looking at the straight-electric and dual-mode options, one key difference is the estimated cost of locomotives. The dual-mode locomotive tends to be more expensive than the straight-electric locomotive. This has a significant impact on the cost of the system, especially if looking at a more widespread implementation of electrification. In addition, the operational costs of dual-mode locomotives would likely be higher than the operational cost of straight-electric locomotives.[51] However, the consideration of operational costs is outside the scope of this analysis.

Exhibit 5-5. Estimated capital costs for rail mainline electrification (Option III)

	Cost of Rail Electrification (Undiscounted 2011 Dollars)	Cost of Locomotives or LSM Helper Cars, Through 2035	Total Capital Cost (Undiscounted 2011 Dollars)
Alternative 1: Straight-Electric Locomotives (Electrified Catenary)	$4.1 B	$9.5 B	$13.7 B
Alternative 2: Dual-Mode Locomotives (Electrified Catenary)	$4.1 B	$15.3 B	$19.4 B
Alternative 3: LSM System*	$4.3 B – $17.3 B	Unknown	Cost Uncertainty*

* Not enough is known about the full project cost of constructing an LSM system to include in the cost analysis.

Other line-haul locomotive emission reduction strategies

In addition to the strategies listed above, prior studies have considered several options to reduce locomotive emissions. However, these strategies are not practical for the SCAB region in the long term; either because they are not technically practical, are not relevant in the long term as the locomotive fleet turns over, or are now mandated by recent ARB or EPA regulations. A selection of additional strategies is summarized here.

- **Retrofit uncontrolled and Tier 0 locomotives with aftertreatment technology.** ARB has explored ways to reduce emissions from units currently in-use installing aftertreatment technologies that pull pollutants from the engine exhaust. This has encountered significant technological problems for deployment, and is not currently feasible. Further, because the baseline locomotive fleet is expected to phase out uncontrolled and Tier 0 locomotives rapidly, this strategy only has a short-term benefit. By 2023 this strategy does not produce any emission benefits. For this reason, the strategy is not evaluated here.

- **Accelerate the rate of Tier 2 locomotive rebuilds.** Locomotive rebuilds are an effective way of reducing emissions in the near term, as existing units can be rebuilt much faster than they can be replaced. However, based on the U.S. EPA's projections, we assume that all Tier 2 locomotives will be rebuilt by 2019, so this strategy will have no impact beyond that year. Because this strategy has only short-term benefits and would not contribute significantly toward meeting air quality goals in 2023 and beyond, we do not analyze its impacts.

[51] California Environmental Associates, Memo to Annie Nam, Southern California Association of Governments. October 14, 2011.

- **Repower regional locomotives with Low-Emitting Locomotive (LEL) engines.** In its review of locomotive emission reduction strategies, ARB identified a strategy of replacing engines in older regional locomotives with new two- or four-stroke locomotive engines that meet or exceed Tier 2 standards. At the time, ARB believed that LEL engines might become available between 2010 and 2012. The technical feasibility and market readiness of LEL engines should be further explored before proceeding with this strategy.

- **Install anti-idling devices on line-haul locomotives.** While anti-idle technology is a cost effective way to reduce emissions, the potential benefit of this strategy in Southern California is limited due to ARB and EPA regulations that already include anti-idling provisions. EPA's 2008 regulations require that all new locomotives come equipped with anti-idling technology to reduce unnecessary idling. In addition, ARB's 2005 statewide railyard agreement placed limits on locomotive idling. Due to this agreement, anti-idle devices have been installed on 99 percent of intrastate locomotives.[52]
- **Rebuild Tier 0 and pre-Tier 0 locomotives to meet Tier 0+ standards.** EPA's 2008 regulations created additional standards for rebuilt locomotives. Engines in Tier 0 are required to meet enhanced Tier 0+ standards that require a 44 percent reduction in HC and PM and a 10 percent reduction in NOx. Tier 0+ upgrade kits may be extendable to pre-Tier 0 locomotives as well. ARB has identified this strategy as a cost-effective option for reducing emissions from regional line-haul locomotives. However, because line-hauls are repowered on a cycle of approximately 8 years, all Tier 0 locomotives would be upgraded to Tier 0+ by 2023 in the baseline scenario. Because of this, the strategy would have no impact in 2023 and 2035.

5.2. Switcher locomotive strategies

This section analyzes the benefits and costs of several emission reduction strategies for switcher locomotives, as compared to the baseline of emission levels that reflects no additional regulation or public investment in emission control measures.

Strategy 1: Replace Tier 0 and pre-Tier 0 switchers with Tier 4 Switchers

Switcher locomotives are often Tier 0 and pre-Tier 0 units that have been retired from line-haul operation. Railyard emissions can be reduced by replacing these high emission locomotives with Tier 4 switcher locomotives that rely on clean engines and exhaust aftertreatment to meet the most stringent EPA standards. Tier 4 switchers are scheduled to be introduced between 2015 and 2017.

Emissions Impact

The goal of this strategy is to replace all Tier 0 and pre-Tier 0 switchers with Tier 4 locomotives by 2023, to completely eliminate Tier 0 / pre-Tier 0 from the fleet in that year. A strategy to accelerate GenSet introduction would greatly reduce criteria pollutant emissions; reducing NOx and PM2.5 emissions by 49 and 45 percent in 2023, respectively. This strategy does not affect greenhouse gas emissions, since the fuel efficiency of each engine technology is projected to remain constant in future years. These emission trends are shown in Exhibit 5-6.

By 2035, the benefits of this strategy are eliminated compared to the baseline, once the baseline switcher fleet eliminates Tier 0 locomotives through fleet turnovers. In this year, there is no emission benefit for any pollutant, compared to the baseline emissions.

[52] Air Resources Board, *Technical Options to Achieve Additional Emissions and Risk Reductions from California Locomotives and Railyards*, August 2009.

Exhibit 5-6. Emission Reductions from replacing Tier 0 with Tier 4 Switchers (tons per day)

	NOx			PM2.5			CO2		
Year	Switcher baseline	With Strategy	% Change	Switcher baseline	With Strategy	% Change	Switcher baseline	With Strategy	% Change
2010	1.37	1.37	0%	0.041	0.041	0%	94	94	0%
2023	0.68	0.35	-49%	0.017	0.009	-45%	123	123	0%
2035	0.37	0.37	0%	0.010	0.010	0%	153	153	0%

Cost

The costs of Tier 4 single-engine switcher locomotives have not been clearly established. EPA estimates the cost of Tier 4 line-haul locomotives at $3 million each. While switcher locomotives have smaller engines and less power than line-hauls, the costs of each loco type are assumed to be comparable.

In total, this strategy would replace 29 Tier 0 locomotives with Tier 4 units, at a cost of $87 million.

Strategy 2: Repower Tier 3 GenSet switchers with new Tier 4 nonroad engines

UP and BNSF currently operate 61 GenSet switchers within SCAB. GenSets are typically powered by a bank of three nonroad engines. Nonroad engines are typically found in off-road heavy-duty equipment such as construction, mining, and cargo handling equipment. EPA regulates nonroad engine emissions using a Tier structure more stringent than locomotive engine standards.

EPA's 2005 ruling on nonroad engines introduced Tier 4 nonroad engine standards that phase into effect between 2011 and 2015. The agency expects manufacturers to meet Tier 4 standards by introducing exhaust treatment controls such as DPF and SCR. While new nonroad engines must meet Tier 4 PM standards in 2011, the Tier 4 NOx requirements are implemented in phases from 2011 to 2014.[53] By 2015, new-model GenSets will by fully compliant with Tier 4 nonroad engine standards.

The goal of this strategy is to update all Tier 3 GenSet switchers with Tier 4 nonroad engines by year 2023. ARB estimates that switch locomotives with Tier 3 nonroad engines would need to be repowered every 10 to 15 years. This strategy would accelerate the length of time before repowering to as little as 8 years in order to fully upgrade the existing GenSet fleet by 2023. Because all GenSets after 2015 will meet Tier 4 standards when introduced into the fleet, this strategy only needs to target the existing 61 GenSets operating in Southern California and new units purchased before 2015.

Emissions Impact

In year 2023 the baseline fleet will contain 108 GenSet switch locomotives, 71 of which are built to Tier 3 standards. In this strategy all 71 Tier 3 GenSets are upgraded to Tier 4 by 2023, reducing NOx by 27% and PM2.5 by 36% in that year. By 2035, while the net reductions remain the same, the effectiveness of the strategy increases to 50% reduction in NOx and 62% reduction in PM2.5. These emission reductions are shown in Exhibit 5-7.

[53] US EPA, "Final Regulatory Impact Analysis: Control of Emissions from Nonroad Diesel Engines." EPA420-R-04-007, May 2004.

Exhibit 5-7. Emission reductions from repowering GenSets with Tier 4 nonroad engines (tons per day)

	NOx			PM			CO2		
Year	Switcher baseline	With Strategy	% Change	Switcher baseline	With Strategy	% Change	Switcher baseline	With Strategy	% Change
2010	1.37	1.37	0%	0.041	0.041	0%	94	94	0%
2023	0.68	0.50	-27%	0.017	0.011	-36%	123	123	0%
2035	0.37	0.18	-50%	0.010	0.004	-62%	153	153	0%

Cost

ARB estimates that a GenSet switcher could be upgraded to Tier 4 at an incremental cost of $200,000 over Tier 3 rebuilds. This cost is based on estimates of the cost of switch components, including engines, generators, cooling systems, and aftertreatment. This strategy would incur additional capital costs by accelerating the pace of rebuilds. Instead of amortizing the rebuild costs over 10 to 15 years in the base case, costs would be spread over 8 years. However, these indirect costs are excluded from this analysis. In total, the cost of upgrading 71 Tier 3 GenSets to Tier 4 is $14.2 million.

Additional switch locomotive strategies not considered in this analysis

- **Upgrade Tier 0 and uncontrolled switchers to Tier 0+ standards.** A rebuild strategy targeted at Tier 0 and uncontrolled locomotives would result in engine upgrades that would not otherwise occur in the base case. While the current regulations only apply to Tier 0 units, ARB believes that rebuild kits will become available to upgrade uncontrolled locomotives to the same Tier 0+ standards. However, under current baseline projections, the number of uncontrolled and Tier 0 locomotives would be very small in 2023 and zero in 2035, resulting in very small emissions benefits in those years.

- **Upgrade existing GenSet switchers with exhaust aftertreatment.** ARB proposes this strategy as part of a package of railyard reduction measures.[54] However, the retrofit equipment needed for this strategy is not currently available. This strategy is also less effective than Strategy 2, in which GenSets would be upgraded with Tier 4 nonroad engines. The Tier 4 upgrade would produce greater emissions reductions at a similar cost, and is more technically feasible.

- **Outfit Tier 0 and uncontrolled switchers with aftertreatment DPF and SCR devices.** Section 5.1 discusses the limitations of installing aftertreatment in line-haul locomotives. The same technical challenges exist for switchers, and ARB analysis has shown the potential benefits of upgrading switchers to be smaller. For this reason, an aftertreatment strategy is not quantified for switch locomotives. The same technical challenges exist for switchers as for line-haul locomotives, and ARB analysis has shown the potential benefits of upgrading switchers to be much smaller. For this reason, an aftertreatment strategy is not quantified for switch locomotives.

5.3. Summary of Environmental Benefits and Costs

Exhibit 5-8 summarizes the emission reduction strategies quantified in this report. Note that summary table combines all line-haul and switcher emissions into a single total value, to compare total benefits across all strategies. The values in this table may not match the values in previous tables, which only show baseline and benefits for line-haul or switchers, depending on the strategy.

[54] Air Resources Board, *Technical Options to Achieve Additional Emissions and Risk Reductions from California Locomotives and Railyards*, August 2009.

The summary table shows that in 2035, electrification results in NOx reductions that are nearly double the accelerated Tier 4 strategies, although only slightly larger PM2.5 reductions. Electrification is the only one of these strategies that would reduce CO2 emissions. The capital costs of electrification are 2 to 4 times higher than the upper bound costs of the accelerated Tier 4 strategies.

Exhibit 5-8. Summary of Locomotive Strategy Emissions Impacts and Costs, in 2023 and 2035, SCAB

Strategy	Freight Locomotive Emissions (tpd)						Capital Cost
	NOx		PM2.5		CO2		
	Emissions	Change	Emissions	Change	Emissions	Change	
2023							
Baseline	15.9		0.33		1,967		-
Tier 4 100% by 2023	5.9	-10.0	0.11	-0.22	1,967	0	$0 - $8.5B
Tier 4 100% by 2035	11.9	-4.0	0.21	-0.12	1,967	0	$0 - $4.9B
Mainline Electrification	15.9	0	0.33	0	1,967	0	N/A
Replace Tier 0 Switchers with Tier 4	15.6	-0.33	0.32	-0.01	1,967	0	$87 million
Repower GenSets with Tier 4 nonroad	15.7	-0.18	0.32	-0.01	1,967	0	$14.2 million
2035							
Baseline	13.1		0.24		2,906		-
Tier 4 100% by 2023	7.3	-5.8	0.12	-0.12	2,906	0	$0 - $8.5B
Tier 4 100% by 2035	7.3	-5.8	0.12	-0.12	2,906	0	$0 - $4.9B
Mainline Electrification	2.6	-10.5	0.09	-0.15	914	-1,993	$13.7B-19.4B
Replace Tier 0 Switchers with Tier 4	13.1	0	0.24	0	2,906	0	N/A
Repower GenSets with Tier 4 nonroad	12.9	-0.18	0.23	-0.01	2,906	0	$14.2 million

6. Operational and Maintenance Strategies

In addition to the technological oriented strategies for trucks and locomotives discussed in Sections 3 and 5, emissions can also be reduced through strategies that change the way trucks, locomotives, and other vehicles are operated and maintained. This section reviews a number of operational strategies and, where possible, estimates emissions benefits.

Accurately quantifying the emissions impacts of these operational strategies is often difficult, and in many cases the potential emissions benefits are small relative to the technological strategies presented in Sections 3 and 5. Thus, this section describes emissions benefits mostly in qualitative terms, supplemented by order-of-magnitude estimates of emissions benefits for some strategies.

Expansion of On-Dock Rail

Use of on-dock rail eliminates truck VMT and associated emissions by allowing trains to be loaded and unloaded inside marine terminals, thus reducing the need for drayage truck trips between the terminals and intermodal rail yards. The emissions benefits of on-dock rail expansion depend on how the cargo would otherwise have moved. Containers transported via on-dock rail often move long distances between the ports and inland cities (e.g., Chicago); thus, in the absence of on-dock rail service, the cargo would move via a near-dock intermodal facility (ICTF, SCIG, etc.) or off-dock facility (Hobart, etc.).

The emission benefits of an increase in on-dock rail use have been estimated in a number of other studies.[55] The benefits of this strategy decline in the future as the drayage truck fleet becomes cleaner. In addition, the reduction in truck emissions due to increased on-dock rail is partially offset by an increase in locomotive activity. Nonetheless, it is expected that on-dock rail expansion would result in net emissions benefits.

For the purposes of SCAG's RTP, the potential emissions benefits of this strategy depend on the ability to increase on-dock rail beyond current baseline assumptions. The percent of port containerized cargo loaded directly to/from rail on-dock has been growing, from about 20% in 2005 to about 23.5% in 2010. The ports have a goal of achieving 35%.

Most container terminals at the Ports of Los Angeles and Long Beach are already served by on-dock rail. The Quick Trip model that estimates daily container trips generated at each marine terminal of the ports assumes about 29% of container throughput in TEUs (excluding empties) to be carried by on-dock rail in 2035. About 12% of this is assumed for the Port of Long Beach terminals and 17% for the port of Los Angeles terminals. By 2035, the Pier B facility at the Port of Long Beach, which is currently a storage and staging area for trains serving the on-dock rail yards, is expected to be redeveloped to support increased use of on-dock rail. This project has the potential to increase the efficiency of on-dock rail at the port's terminals, increasing the Port of Long Beach's on-dock share by about 5% beyond the values assumed in the Quick Trip model.

The ports have indicated that these assumptions that underlie the Heavy Duty Truck model reflect the maximum possible on-dock rail use at the Ports. Additional use of on-dock rail is limited by factors such as shipper and marine vessel logistics (transloading, transportation costs, etc.), railroad operations (equipment availability, train schedules, and steamship line contracts/arrangements), and terminal operations/congestion. Therefore, no emission reductions are calculated for this strategy.

[55] See Cambridge Systematics, *Port Truck Trip Reduction Strategies*, Prepared for the Port of Long Beach and Port of Los Angeles, 2006; ICF International, Analysis of *Goods Movement Emission Reduction Strategies*, Task 1 Report, Prepared for SCAG, January 2008.

Expansion of Near-Dock Rail

Near-dock rail terminals provide rail accessibility to import and export cargo, using drayage trucks for the connection to and from port terminals. Expansion of near-dock rail will reduce truck VMT and emissions by eliminating the need to access more distant off-dock rail facilities. Two near-dock rail projects are currently undergoing environmental review: BNSF's Southern California International Gateway (SCIG) and modernization of UP's Intermodal Container Transfer Facility (ICTF). The assumptions that underlie SCAG's heavy-duty truck model reflect the completion of these facilities. These assumptions are not meant to prejudge the environmental investigations; they are only used as a tool for estimating potential emission reductions.

The emissions benefits of near-dock rail facility expansion depend on how these projects would alter truck travel patterns. In previous analyses, it has been assumed that all trips involving the new SCIG terminal are diverted trips from the Hobart intermodal terminal near downtown Los Angeles.[56] Because the use of a near-dock terminal requires a drayage move like off-dock service, the number of truck trips would not be significantly affected by this strategy. VMT however, would be reduced due to the shorter distance from the ports to the SCIG terminal (4 miles), versus the distance to the Hobart terminal (24 miles).

Grade Separation of Rail Intersections

The purpose of this strategy is to reduce emissions at a railroad crossing by building a grade-separated interchange that allows trains and vehicles to pass through without conflicting. This would eliminate any emissions currently caused by vehicle delay and idling at a signalized railroad intersection. Thus the emission benefits of grade separation are equal to the emissions caused by delay at an existing signalized intersection. This section provides an overview analysis of the benefits of grade separation, with a general characterization of emission benefits. For additional precision, each intersection would require study individually to analyze traffic patterns, configuration options, and delay impacts.

This analysis is based on a standard methodology[57] to calculate vehicle delay at rail-road grade crossings. The methodology is applied for each train crossing event, whose sum for all trains over a 24-hour period gives an estimate of daily vehicle hours of delay. Total idling emissions were calculated by multiplying total road traffic delay for each vehicle category by idling emission factors, as provided by EMFAC 2007. The traffic share of each vehicle category was obtained from EMFAC for the SCAB region, calculated using the total VMT in the region for each vehicle type.

At the time this report was written, a list of 60 potential grade separation projects for the SCAG region with sufficient data for analysis of traffic delay and emissions benefits was available. The emissions benefits shown below are therefore representative of the potential emissions benefits associated with a grade separation strategy. The final 2012 RTP will contain a complete list of grade separation projects for both the constrained plan and the strategic plan. Exhibit 6-1 shows, for 2010 and 2035, the highest and lowest per-project emission benefits, the mean emissions benefit, and the total benefit for all 60 analyzed projects. The average daily emission reduction per project in 2010 is 37.3 grams of NOx, 1.3 grams of PM2.5, and 29.9 pounds of CO_2. By 2035, the average daily emission reduction per project would be 212.5 grams of NOx, 4.4 grams of PM2.5, and 128.1 pounds of CO_2.

[56] Fischer, M., Hicks G., Cartwright, K. (2006): Performance Measure Evaluation of Port Truck Trip Strategies. National Urban Freight Conference, Long Beach, California.

[57] Surface Transportation Board (2003): Construction and Operation of a Rail Line from the Bayport Loop in Harris County, Texas – Draft Environmental Impact Statement. Finance Docket No. 34079

Exhibit 6-1. Emission Benefits of Potential Rail Crossing Grade Separation Projects

	2010 Emissions			2035 Emissions		
	NOx (g/day)	PM2.5 (g/day)	CO2 (lbs/day)	NOx (g/day)	PM2.5 (g/day)	CO2 (lbs/day)
Highest Project	126.2	4.5	101.4	750.5	15.4	452.4
Lowest Project	0.2	0.0	0.2	1.3	0.0	0.8
Mean	37.3	1.3	29.9	212.5	4.4	128.1
Total	2,235.8	80.2	1,796.1	12,751.5	261.3	7,687.1

The cost of a grade separation project varies greatly depending on site-specific details. A 2006 study of the Alameda Corridor East estimated the average cost of intersection grade-separation projects to be $35 million.

Off-Peak Delivery Program

Shifting vehicles from congested to uncongested facilities or time periods reduces emissions in two ways: shifted trucks generate fewer emissions because they move to free flow conditions; and the remaining vehicles generate fewer emissions because traffic flow is improved. Therefore, while this strategy does not reduce vehicle miles traveled, it can contribute to reduced congestion along facilities like the I-710 on weekdays by shifting traffic from peak to non-peak hours. The existing PierPass program at the ports use a fee/rebate system to encourage trucks to shift port access trips from peak-hours to off-peak night periods and weekends. Since the program was established in 2005, more than 2 million truck trips have been diverted from daytime hours to off-peak hours and weekends, and total weekday volume has declined due to a shift from weekdays to weekends. A study by Giuliano and O'Brien estimates the total diversion to off-peak hours resulting from the existing PierPass program to be in the range of 22-30% of all truck moves, accounting for the many exemptions to the fee.[58] The program has resulted in a total weekday reduction of 12%-16% of truck volumes on the I-710 alone and has reduced truck waiting times inside port terminals.[59]

Given the success of PierPass, it is clear that shippers and carriers have some flexibility to shift travel time. Expanding the PierPass program could encourage an additional shift from peak to off-peak hours. However, there is a limit to the share of truck movements that can be pushed into the night hours based on gate capacity at the ports. The baseline traffic assumptions by shift in the Quick Trip model for 2035 are 60% daytime, 20% night, and 20% hoot shifts. The night time operations are already assumed to be more aggressive than the current PierPass progam; therefore, a further shift of peak hour truck trips may not be possible. In addition, it is difficult to accurately forecast traffic flow and emissions effects of temporal shifts on the I-710 at this time, given the on-going environmental review for the I-710 expansion project. Therefore, no emission reductions have been calculated for this strategy.

Another strategy to achieve a similar impact by reducing peak period truck movements is to require large warehouses and other facilities that receive goods to operate in the off-peak hours. As part of a SCAQMD rule, a shipper-receiver program was proposed in the city of Los Angeles in the early 1990s to require

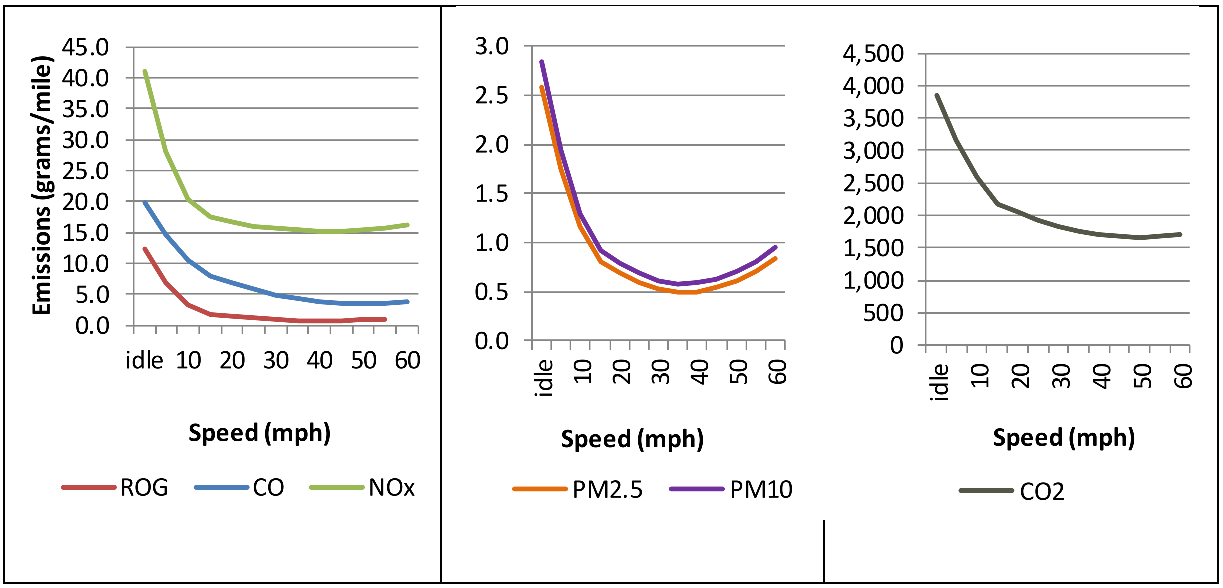
[58] Giuliano, Genevieve and T. O'Brien (2009), Responding to Increasing Port-Related Freight Volumes: Lessons from Los Angeles/Long Beach and other US ports and Hinterlands, in Port Competition and Hinterland Connections, Round Table 143, Transport Research Center, Organization for Economic Cooperation and Development (OECD).

[59] Cambridge Systematics (2005), *Port Truck Trip Reduction Strategies*, Final report, prepared for the Port of Long Beach.

loading docks receive goods in off-peak hours. This would have required businesses to stay open for at least four hours between 8:00 pm and 5:00 am, if five or more shipments were received during peak traffic hours. Shipper-receivers would be limited to five deliveries within the peak traffic hours. If an establishment shipped or received more than eight shipments in the peak, then one-third of the shipments (in excess of five) must be rescheduled to off-peak hours.[60] Such a program may result in economic costs for facilities that may be forced to employ a second operating shift; however, other options may be possible such as providing suppliers with access to an unstaffed safe storage facility.

Such a strategy is promising because reducing peak hour truck traffic by even a small amount can result in considerable reduction in emissions. Exhibit 6-2 shows how the emission factors for Heavy heavy-duty trucks (HHDT) vary by speed bin in the EMFAC2007 model for the year 2010. Up to about 35 mph, improving average speeds will reduce per-mile emission rates. However, note that increasing average speed above 40 mph produces higher PM emission in EMFAC.

Exhibit 6-2. Emission factors by speed for HHDVs in 2010, South Coast Air Basin



Source: EMFAC2007 (see Appendix B)

Aside from the emissions benefits of congestion reduction, shifting emissions to evening and night periods would also be expected to result in less ozone formation as compared to daytime emissions. However, a recent study using data from two cities in California suggests that shifting truck logistic operations to night-time hours corresponding to the PierPASS program at the ports could potentially have the unintended consequence of higher 24-hour average concentrations of diesel exhaust pollutants, depending on local meteorology and traffic speeds.[61] These effects are complex, and properly understanding any ozone impacts requires regional air quality modeling, which is outside the scope of this study.

[60] Nelson, Arthur C., S. Siwek, Randall L. Guensler, K. Michelson (1991), *Managing Trucks for Air Quality: Current Work in Progress*, Transportation Research Record (1312), pp. 50-58.

[61] Sathaye, Nakul, R. Harley, S. Madanat (2010), Unintended environmental impacts of nighttime freight logistics activities, *Transportation Research Part A: Policy and Practice*, Volume 44, Issue 8, pages 642-659.

Increased Enforcement of Anti-Idling Regulations

ARB regulations limit truck idling to five minutes at loading docks, in queues at the ports, at distribution centers, and on the street. While there have been studies of long-duration idling at truck stops and highway rest areas, very limited data exist on the extent of idling in urbanized areas. ARB conducted an analysis in 2002 of truck idling activity, based on GPS data from a sample of instrumented vehicles. The data from 84 Heavy heavy-duty trucks (HHDT) and 34 Medium heavy-duty trucks (MHDT) found that the HHDT fleet averaged 105 minutes of idling per day, or 21 minutes per trip. The MHDT fleet average was 6 minutes per day.[62]

Exhibit 6-3 shows data on the number of truck inspections and citations issued by ARB in 2010 for trucks violating the state anti-idling rule. The failure rate reported by ARB suggests that violations of the state idling regulation are extensive, particularly in Southern California. However, given that there are approximately 160,000 HDVs in the South Coast Air Basin, it is also clear that the limited number of annual inspections currently conducted by ARB covers only a small fraction of total truck population. So it is difficult to assess how representative these statistics are.

Exhibit 6-3. ARB Commercial Vehicle Idling Enforcement Activities, 2010

	Northern CA	Southern CA	Border	Total	Program to Date Statewide
Total Number of Inspections	3,580	1,256	2,045	6,881	52,563
Total Number of Citations (citations minus rescinded)	179	411	393	1,505	5,987
Failure Rate (citations/number of trucks inspected)	5%	33%	19%	22%	11%

Source: CARB, Heavy Duty Diesel Enforcement Section

Assuming that HHDTs receiving a citation actually idle an average of 21 minutes per trip or 105 minutes per day (using ARB's average estimate of 5 HHDT trips per day), better enforcement of the anti-idling rule could result in a reduction of 16 minutes per HHDT trip or 80 minutes per day. Exhibit 6-4 shows the average annual reduction in emissions per truck associated with this potential reduction in idling in 2023 and 2035. (See Appendix B for emission factors.)

Exhibit 6-4. Per Truck Emissions Reduction from Increased Enforcement of ARB Idling Rule (grams per truck per day)

Year	NOx	PM2.5	CO2
2023	162	0.13	8,717
2035	163	0.14	8,735

It is difficult to estimate the potential region-wide benefit of increased idling enforcement. To establish an upper bound, we assume that 100,000 HHDVs operate in the SCAB in 2023 (consistent with EMFAC) and that 11% of these trucks consistently violate the idling regulation (11% is the statewide failure rate for 2010). If increased enforcement reduces idling by these vehicles an average of 80 minutes per day over 250 working days per year, the total emission reduction in 2023 would be about 2 tons per day NOx and 0.0016 tons per day PM2.5, as shown in Exhibit 6-5. Emission reductions would increase approximately 50% by 2035 as the truck population grows.

[62] "Major Revision: Extended Idle for Heavy Heavy-Duty Diesel Trucks," CARB, available at: http://www.arb.ca.gov/msei/onroad/latest_revisions.htm#hhddt_idle

Exhibit 6-5. Maximum Potential Emission Reduction from HHDV Idling Enforcement in SCAB, tons per day

Year	NOx	PM2.5	CO2
2023	1.96	0.0016	105
2035	2.94	0.0024	158

Conditional Use Permits for Warehouses

Local governments can issue conditional use permits (CUPs) to new warehouses, requiring them to implement specific emissions mitigation measures. Examples of measures that can be required as part of a CUP include:

- Installation of on-site electric hook-ups to eliminate the idling of main and auxiliary engines during loading and unloading of cargo and when trucks are not in use
- Requirement for all new truck terminals, warehouses and other shipping facilities receiving refrigerated trailers and with more than 50 truck trips per day to provide electrical hookups for the refrigerated units to reduce idling emissions when the truck is parked at the loading dock.
- Maintenance of equipment and vehicle engines in good condition and in proper tune as per manufacturers' specifications.
- Restricting operation to "clean" trucks – i.e., require or provide incentives for the use of alternative clean fuel such as natural gas or electric drive technologies (see Section 3)
- Restricting truck idling to five minutes or less – this has been included in several CUPs in California

Although the state has a 5 minute idling limit, data from ARB presented above makes clear that extended idling remains a problem. We analyze a strategy that would reduce truck idling through CUPs implemented at new warehouses.

In 2008, about 694 million square feet of regional warehouse space were needed to accommodate the port related and non-port related cargo volumes. By 2035, the rise in container volumes at the ports and domestic cargo in the SCAG region would require an estimated 1.25 billion square feet of warehouse space, or about 556 million square feet more than what was needed in 2008.[63]

Using average truck trip generation rates for warehousing and distribution facilities, the volume of truck traffic associated with the additional warehousing space required in 2035 can be estimated. According to a study conducted for the San Bernardino Associated Governments (SANBAG) in 2005, average truck trip generation, including in-bound and out-bound trips, was 0.532 trips per weekday per 1,000 square feet of warehousing space.[64] This represents an average of 0.266 round trips per truck per weekday. We can further assume an "adoption rate" for the CUPs such that 50% of all regional warehousing space in 2035 is covered by the CUP restrictions. Considering reduction in idling at warehouses to be one potential measure that has already been included in several CUPs in California, Exhibit 6-7 shows the reduction in emissions possible if idling per truck is reduced by 5 minutes at new warehousing facilities.

[63] Cambridge Systematics and Economics & Politics (2010), Industrial Space in Southern California: Future Supply and Demand for Warehousing and Intermodal Facilities, SCAG Goods Movement Study Task 5 Final report, prepared for Southern California Association of Governments, p. 3-3.

[64] Crain & Associates, San Bernardino/Riverside County Warehouse/distribution Center Vehicle Trip Generation Study (Inland Empire Study), Prepared for NAIOP at the request of SANBAG, January 2005.

Exhibit 6-7. Potential Reduction in Idling Emissions through CUPs for New Warehouses (tons per day)

Year	NOx	PM2.5	CO2
2035	0.75	0.0006	40.4

Truck Inspection and Maintenance Program

As a truck ages, there is an increase in the wear and deterioration of engine parts and emission controls. Over the life of a truck, wear and deterioration of engine parts and emission control equipment can cause emissions to increase. Proper maintenance can significantly reduce the increase in emissions as a truck ages. ARB assumes deterioration rates in the EMFAC model. Beginning with model year 2010, ARB regulation requires new trucks be to equipped with on-board diagnostics (OBD), which will reduce deterioration. For HHDVs, these factors are shown in Exhibit 6-8, expressed in grams/mile per 10,000 miles accumulated.

Exhibit 6-8 HHDV Emission Rate Deterioration Factors in EMFAC (grams/mile per 10,000 miles)

Type	NOx	PM
2010+	0.041	0.001
2010+/OBD	0.032	0.0007

Source: California Air Resources Board, EMFAC Modeling Change Technical Memo, "Revision of Heavy Heavy Duty Diesel Truck Emission Factors and Speed Correction Factors," Table 9, October 20, 2006.

Exhibit 6-9 shows the "Zero Mile Rates" for NOx and PM, along with emission rates for vehicles with 100,000 and 500,000 miles accumulated. These results illustrate the effects of the OBD requirement.

Exhibit 6-9 HHDV Emission Rates by Mileage Accumulation (grams per mile)

Truck mileage accumulation	Type	NOx	PM
0 (new vehicle)		1.14	0.035
100,000	2010+	1.55	0.05
	2010+/OBD	1.46	0.04
500,000	2010+	3.19	0.09
	2010+/OBD	2.74	0.07

Currently, no in-use truck I&M programs exist in California. ARB studies show that most HHDV engines would be rebuilt multiple times during their lives and each rebuild event could eliminate the emission increase attributable to malmaintenance, particularly for older model year trucks. ARB studies also show that increased diesel engine durability has enabled many engines to run 750,000 to 1,000,000 miles before needing a rebuild.

ARB makes the basic assumption that the emissions from diesel powered trucks remain stable in the absence of tampering and malmaintenance (T&M). For a given pollutant, the T&M impact rate is the percentage increase in emissions over the level that vehicles would have produced if they had all been well maintained and free of tampering. A study conducted for Sacramento offers information on coverage of I&M programs, finding that about 45% of the vehicles registered in Sacramento County (about

340,000 vehicles) were measured at least once.[65] Another study suggests that about 15%-20% of the fleet is typically likely to be in a state of malmaintenance.[66]

To estimate the emission benefits of this strategy, we assume that HHDVs in the SCAB have an average accumulated mileage of 500,000 miles. Further, we assume that 20% of the vehicle fleet will be malfunctioning – the high end of the Sacramento study described above. We assume that upon inspection, emissions from trucks in violation would return to their original zero-mile rate. The emissions avoided by such an HHDV I&M program are shown in Exhibit 6-10.

Exhibit 6-10. Emissions Reduction from In-Use HHDV I&M Program (tons per day)

Year	NOx	PM2.5	CO2
2023	8.13	0.22	N/A
2035	9.87	0.26	N/A

Transportation System Management

A key category of operational strategies are transportation system management measures that reduce roadway congestion and improve traffic flow. In most cases, traffic flow improvements result in lower emissions. These strategies include:

- Bottleneck relief/gap closure projects
- Ramp metering
- Incident management
- Traffic signal timing
- Variable message signs and other traveler information systems

Analysis of the emissions benefits of these strategies is challenging and requires use a regional travel model and/or traffic simulation tools. This report does not analyze these types of strategies.

Summary of Operational and Maintenance Strategy Emissions Benefits

Exhibit 6-11 summarizes the emissions benefits of the four operational and maintenance strategies quantified in this section. An inspection and maintenance program for heavy heavy-duty trucks would have by far the largest emissions impact of the four strategies, since it would affect a significant portion of all truck travel in the Basin. The NOx and PM2.5 emissions reductions represent 11% and 8% of the baseline heavy-duty truck emissions forecast. The LCV and CUP strategies have relatively small benefits as they have been defined here, since they affect only a small portion of truck activity. The emission reductions from these strategies are 0.5% to 1% of the baseline heavy-duty truck emissions forecast.

[65] Radian Corporation, Draft Final Report: Evaluation of the California Pilot Inspection/Maintenance (IM) Program, 1995, quoted in Hubbard (1997).
[66] Hubbard, Thomas N.. 1997. Using Inspection and Maintenance Programs to Regulate Vehicle Emissions. *Contemporary Economic Policy*. 15(2): 52-62.

Exhibit 6-11. Summary of Emissions Benefits of Operational and Maintenance Strategies

Strategy	2023 Emission Reduction (tpd)			2035 Emission Reduction (tpd)		
	NOx	PM2.5	CO2	NOx	PM2.5	CO2
Expansion of On-Dock Rail	N/A	N/A	N/A	N/A	N/A	N/A
Expansion of Near-Dock Rail	N/A	N/A	N/A	N/A	N/A	N/A
Grade Separation of Rail Intersections (total of 10 most congested)	0.001	0.00004	0.4	0.006	0.0001	1.7
Off-Peak Delivery Program	N/A	N/A	N/A	N/A	N/A	N/A
Increased Enforcement of ARB Idling Rule	2.0	0.0016	105	2.9	0.0024	158
Conditional Use Permits for New Warehouses	N/A	N/A	N/A	0.75	0.0006	40.4
HHDV Inspection & Maintenance Program	8.1	0.22	N/A	9.9	0.26	N/A
Transportation System Management	N/A	N/A	N/A	N/A	N/A	N/A

7. Non-Air Impacts and Mitigation Strategies

7.1. Noise

Background

Before discussing goods movement noise impacts and mitigation, this section introduces fundamental environmental noise concepts.

Sound, Noise, and Acoustics

Sound can be described as the mechanical energy of a vibrating object transmitted by pressure waves through a liquid or gaseous medium (e.g., air) to a hearing organ, such as a human ear. *Noise* is defined as loud, unexpected, or annoying sound.

In the science of acoustics, the fundamental model consists of a sound (or noise) source, a receiver, and the propagation path between the two. The loudness of the noise source and obstructions or atmospheric factors affecting the propagation path to the receiver determine the sound level and characteristics of the noise perceived by the receiver. The field of acoustics deals primarily with the propagation and control of sound.

Frequency

Continuous sound can be described by frequency (pitch) and amplitude (loudness). A low-frequency sound is perceived as low in pitch. Frequency is expressed in terms of cycles per second, or Hertz (Hz) (e.g., a frequency of 250 cycles per second is referred to as 250 Hz). High frequencies are sometimes more conveniently expressed in kilohertz (kHz), or thousands of Hz. The audible frequency range for humans is generally between 20 Hz and 20,000 Hz.

Sound Pressure Levels and Decibels

The amplitude of pressure waves generated by a sound source determines the loudness of that source. Sound pressure amplitude is measured in micro-Pascals (mPa). One mPa is approximately one hundred-billionth (0.00000000001) of normal atmospheric pressure. Sound pressure amplitudes for different kinds of noise environments can range from less than 100 to 100,000,000 mPa. Because of this huge range of values, sound is rarely expressed in terms of mPa. Instead, a logarithmic scale is used to describe sound pressure level (SPL) in terms of decibels (dB). The threshold of hearing for young people is about 0 dB, which corresponds to 20 mPa.

Addition of Decibels

Because dBs are logarithmic units, SPL cannot be added or subtracted through ordinary arithmetic. Under the dB scale, a doubling of sound energy corresponds to a 3 dB increase. In other words, when two identical sources are each producing sound of the same loudness, the resulting sound level at a given distance would be 3 dB higher than one source under the same conditions. For example, if one automobile produces an SPL of 70 dB when it passes an observer, two cars passing simultaneously would not produce 140 dB—rather, they would combine to produce 73 dB. Under the dB scale, three sources of equal loudness together produce a sound level 5 dB louder than one source.

A-Weighted Decibels

The dB scale alone does not adequately characterize how humans perceive noise. The dominant frequencies of a sound have a substantial effect on the human response to that sound. Although the intensity (energy per unit area) of the sound is a purely physical quantity, the loudness or human response is determined by the characteristics of the human ear.

Human hearing is limited in the range of audible frequencies as well as in the way it perceives the SPL in that range. In general, people are most sensitive to the frequency range of 1,000–8,000 Hz and perceive sounds within that range better than sounds of the same amplitude in higher or lower frequencies. To approximate the response of the human ear, sound levels of individual frequency bands are weighted, depending on the human sensitivity to those frequencies. Then, an “A-weighted” sound level (expressed in units of dBA) can be computed based on this information.

The A-weighting network approximates the frequency response of the average young ear when listening to most ordinary sounds. When people make judgments of the relative loudness or annoyance of a sound, their judgments correlate well with the A-scale sound levels of those sounds. Noise levels for environmental noise reports are typically reported in terms of A-weighted decibels or dBA. Exhibit 7-1 describes typical A-weighted noise levels for various noise sources.

Exhibit 7-1. Typical A-Weighted Noise Levels

Common Outdoor Activities	Noise Level (dBA)	Common Indoor Activities
	— 110 —	Rock band
Jet flying at 1,000 feet		
	— 100 —	
Gas lawn mower at 3 feet		
	— 90 —	
Diesel truck at 50 feet at 50 mph		Food blender at 3 feet
	— 80 —	Garbage disposal at 3 feet
Noisy urban area, daytime		
Gas lawn mower, 100 feet	— 70 —	Vacuum cleaner at 10 feet
Commercial area		Normal speech at 3 feet
Heavy traffic at 300 feet	— 60 —	
		Large business office
Quiet urban daytime	— 50 —	Dishwasher next room
Quiet urban nighttime	— 40 —	Theater, large conference room (background)
Quiet suburban nighttime		
	— 30 —	Library
Quiet rural nighttime		Bedroom at night
	— 20 —	
		Broadcast/recording studio
	— 10 —	
Lowest threshold of human hearing	— 0 —	Lowest threshold of human hearing

Source: California Department of Transportation, 2009.

Human Response to Changes in Noise Levels

As discussed above, doubling sound energy results in a 3 dB increase in sound. However, given a sound level change measured with precise instrumentation, the subjective human perception of a doubling of loudness will usually be different than what is measured.

Under controlled conditions in an acoustical laboratory, the trained, healthy human ear is able to discern 1 dB changes in sound levels when exposed to steady, single-frequency (“pure-tone”) signals in the mid-frequency (1,000–8,000 Hz) range. In typical noisy environments, changes in noise of 1 to 2 dB are generally not perceptible. However, it is widely accepted that people are able to begin to detect sound level increases of 3 dB in typical noisy environments. Further, a 5 dB increase is generally perceived as a distinctly noticeable increase, and a 10 dB increase is generally perceived as a doubling of loudness. Therefore, a doubling of sound energy (e.g., doubling the volume of traffic on a highway) that would result in a 3 dB increase in sound would generally be perceived as barely detectable.

Noise Descriptors

Noise in our daily environment fluctuates over time. Various noise descriptors have been developed to describe time-varying noise levels. The following are the noise descriptors most commonly used in environmental noise analysis.

- **Equivalent Sound Level (L_{eq}):** L_{eq} represents an average of the sound energy occurring over a specified period. In effect, L_{eq} is the steady-state sound level containing the same acoustical energy as the time-varying sound that actually occurs during the same period. The 1-hour A-weighted equivalent sound level (L_{eq}[h]) is the energy average of A-weighted sound levels occurring during a 1-hour period and is the basis for noise abatement criteria used by Caltrans and FHWA.
- **Percentile-Exceeded Sound Level (L_{xx}):** L_{xx} represents the sound level exceeded for a given percentage of a specified period (e.g., L_{10} is the sound level exceeded 10% of the time, and L_{90} is the sound level exceeded 90% of the time).
- **Maximum Sound Level (L_{max}):** L_{max} is the highest instantaneous sound level measured during a specified period.
- **Day-Night Level (L_{dn}):** L_{dn} is the energy average of A-weighted sound levels occurring over a 24-hour period, with a 10 dB penalty applied to A-weighted sound levels occurring during nighttime hours between 10 pm and 7 am.
- **Community Noise Equivalent Level (CNEL):** Similar to L_{dn}, CNEL is the energy average of the A-weighted sound levels occurring over a 24-hour period, with a 10 dB penalty applied to A-weighted sound levels occurring during the nighttime hours between 10 pm and 7 am and a 5 dB penalty applied to the A-weighted sound levels occurring during evening hours between 7 pm and 10 pm.
- **Sound Exposure Level (SEL):** SEL represents the total amount of sound energy associated with an acoustical event such as a vehicle passby referenced to 1 second.

Individual noise events, such as truck or train pass-bys, are described using single-event and cumulative noise descriptors. For single events, L_{max} is often used, as is SEL. SEL is typically 5 to 10 dB higher than the L_{max}. Cumulative noise descriptors such as L_{eq} can be developed from SEL values. For example if there are five train passbys in one hour, the SEL value for each passby can be used to calculate the one-hour L_{eq} for all five events. If the total number of events in a day is known along with when those events occur, L_{dn} and CNEL values can be calculated.

Sound Propagation

When sound propagates over a distance, it changes in level and frequency content. The manner in which noise reduces with distance depends on the below factors.

Geometric Spreading

Sound from a localized source (i.e., a point source) propagates uniformly outward in a spherical pattern. The sound level attenuates (or decreases) at a rate of 6 dB for each doubling of distance from a point source. Highways consist of several localized noise sources on a defined path and hence can be treated as a line source, which approximates the effect of several point sources. Noise from a line source propagates outward in a cylindrical pattern, often referred to as cylindrical spreading. Sound levels attenuate at a rate of 3 dB for each doubling of distance from a line source.

Ground Absorption

The propagation path of noise from a highway or train track to a receiver is usually very close to the ground. Noise attenuation from ground absorption and reflective-wave canceling adds to the attenuation associated with geometric spreading. Traditionally, the excess attenuation has also been expressed in terms of attenuation per doubling of distance. This approximation is usually sufficiently accurate for distances of less than 200 feet. For acoustically hard sites (i.e., sites with a reflective surface between the source and the receiver, such as a parking lot or body of water), no excess ground attenuation is assumed. For acoustically absorptive or soft sites (i.e., sites with an absorptive ground surface such as soft dirt, grass, or scattered bushes and trees between the source and the receiver), an excess ground-attenuation value of 1.5 dB per doubling of distance is normally assumed. When added to the cylindrical spreading, the excess ground attenuation results in an overall drop-off rate of 4.5 dB per doubling of distance. For point sources the overall drop-off rate is 7.5 dB per doubling of distance.

Atmospheric Effects

Receivers located downwind from a source can be exposed to increased noise levels relative to calm conditions, whereas locations upwind can have lowered noise levels. Sound levels can be increased at large distances (e.g., more than 500 feet) from the highway due to atmospheric temperature inversion (i.e., increasing temperature with elevation). Other factors such as air temperature, humidity, and turbulence can also have significant effects.

Shielding by Natural or Human-Made Features

A large object or barrier in the path between a noise source and a receiver can substantially attenuate noise levels at the receiver. The amount of attenuation provided by shielding depends on the size of the object and the frequency content of the noise source. Natural terrain features (e.g., hills and dense woods) and human-made features (e.g., buildings and walls) can substantially reduce noise levels. Walls are often constructed between a source and a receiver specifically to reduce noise. A barrier that breaks the line of sight between a source and a receiver will typically result in at least 5 dB of noise reduction. Taller barriers provide increased noise reduction. Vegetation between the highway and receiver is rarely effective in reducing noise because it does not create a solid barrier.

Noise Impact Criteria

FHWA and FRA have guidelines and regulations for determining when a highway or rail project is considered to result in a noise impact.

FHWA Regulations

Title 23 Part 772 of the Code of Federal Regulations (23CFR772) identifies procedures for assessing traffic noise for Federal-aid highway projects. A traffic noise impact is considered to occur if noise in the design year with the project would approach or exceed the noise abatement criteria for a given land use activity category. In California "approach" is define as within 1 dB of a noise abatement criterion. A traffic noise impact can also occur if the increase in noise between existing conditions and design year conditions with the project is substantial. In California substantial is defined as 12 dB or greater. Exhibit 7-2 summarizes the FHWA noise abatement criteria.

Exhibit 7-2. Activity Categories and Noise Abatement Criteria (23CFR772)

Activity Category	Activity $L_{eq}[h]$[1]	Evaluation Location	Description of Activities
A	57	Exterior	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B[2]	67	Exterior	Residential.
C[2]	67	Exterior	Active sport areas, amphitheaters, auditoriums, campgrounds, cemeteries, day care centers, hospitals, libraries, medical facilities, parks, picnic areas, places of worship, playgrounds, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, recreation areas, Section 4(f) sites, schools, television studios, trails, and trail crossings.
D	52	Interior	Auditoriums, day care centers, hospitals, libraries, medical facilities, places of worship, public meeting rooms, public or nonprofit institutional structures, radio studios, recording studios, schools, and television studios.
E	72	Exterior	Hotels, motels, offices, restaurants/bars, and other developed lands, properties, or activities not included in A–D or F.
F			Agriculture, airports, bus yards, emergency services, industrial, logging, maintenance facilities, manufacturing, mining, rail yards, retail facilities, shipyards, utilities (water resources, water treatment, electrical), and warehousing.
G			Undeveloped lands that are not permitted.

[1] The $L_{eq}(h)$ activity criteria values are for impact determination only and are not design standards for noise abatement measures. All values are A-weighted decibels (dBA).

[2] Includes undeveloped lands permitted for this activity category.

FRA Guidelines

The Federal Railroad Administration (FRA) relies upon the Federal Transit Administration (FTA) noise impact assessment procedures for assessing improvements to conventional passenger rail lines and stationary rail facilities and horn noise assessment. The procedures are provided in the FTA document entitled "Transit Noise and Vibration Impact Assessment." (FTA 2006).

FTA defines noise impact criteria based on three land use categories, as described in Exhibit 7-3.

Exhibit 7-3. FTA Land Use Categories and Metrics for Rail Noise Impact Criteria

Land Use Category	Noise Metric (dBA)	Description of Land Use Category
1	Outdoor $L_{eq}(h)^*$	Tracts of land where quiet is an essential element in their intended purpose. This category includes lands set aside for serenity and quiet, and such land uses as outdoor amphitheaters and concert pavilions, as well as National Historic Landmarks with significant outdoor use. Also included are recording studios and concert halls.
2	Outdoor L_{dn}	Residences and buildings where people normally sleep. This category includes homes, hospitals and hotels where a nighttime sensitivity to noise is assumed to be of utmost importance.
3	Outdoor $L_{eq}(h)^*$	Institutional land uses with primarily daytime and evening use. This category includes schools, libraries, theaters, and churches where it is important to avoid interference with such activities as speech, meditation and concentration on reading material. Places for meditation or study associated with cemeteries, monuments, museums, campgrounds and recreational facilities can also be considered to be in this category. Certain historical sites and parks are also included.

* L_{eq} for the noisiest hour of transit-related activity during hours of noise sensitivity.

Source: FTA, 2006.

FTA categorizes noise impacts into the following three categories:

- No Impact – On average the introduction of the project will result in an insignificant increase in the number of people highly annoyed by the new project-related noise
- Moderate Impact – An impact where the project-related change in noise is noticeable to most people but may not be sufficient to cause strong, adverse reactions from the community.
- Severe Impact – An impact where a significant percentage of people would be highly annoyed by the new noise (i.e. the project-related increase in noise).

Exhibit 7-4 summarizes FTA noise impact criteria for each land use category.

Exhibit 7-4. Noise Levels Defining Impact for Rail Projects (source: FTA 2006)

Existing Noise Exposure* L_{eq}(h) or L_{dn} (dBA)	Project Noise Impact Exposure,* L_{eq}(h) or L_{dn} (dBA)					
	Category 1 or 2 Sites			Category 3 Sites		
	No Impact	Moderate Impact	Severe Impact	No Impact	Moderate Impact	Severe Impact
<43	< Ambient+10	Ambient + 10 to 15	>Ambient+15	<Ambient+15	Ambient + 15 to 20	>Ambient+20
43	<52	52-58	>58	<57	57-63	>63
44	<52	52-58	>58	<57	57-63	>63
45	<52	52-58	>58	<57	57-63	>63
46	<53	53-59	>59	<58	58-64	>64
47	<53	53-59	>59	<58	58-64	>64
48	<53	53-59	>59	<58	58-64	>64
49	<54	54-59	>59	<59	59-64	>64
50	<54	54-59	>59	<59	59-64	>64
51	<54	54-60	>60	<59	59-65	>65
52	<55	55-60	>60	<60	60-65	>65
53	<55	55-60	>60	<60	60-65	>65
54	<55	55-61	>61	<60	60-66	>66
55	<56	56-61	>61	<61	61-66	>66
56	<56	56-62	>62	<61	61-67	>67
57	<57	57-62	>62	<62	62-67	>67
58	<57	57-62	>62	<62	62-67	>67
59	<58	58-63	>63	<63	63-68	>68
60	<58	58-63	>63	<63	63-68	>68
61	<59	59-64	>64	<64	64-69	>69
62	<59	59-64	>64	<64	64-69	>69
63	<60	60-65	>65	<65	65-70	>70
64	<61	61-65	>65	<66	66-70	>70
65	<61	61-66	>66	<66	66-71	>71
66	<62	62-67	>67	<67	67-72	>72
67	<63	63-67	>67	<68	68-72	>72
68	<63	63-68	>68	<68	68-73	>73
69	<64	64-69	>69	<69	69-74	>74
70	<65	65-69	>69	<70	70-74	>74
71	<66	66-70	>70	<71	71-75	>75
72	<66	66-71	>71	<71	71-76	>76
73	<66	66-71	>71	<71	71-76	>76
74	<66	66-72	>72	<71	71-77	>77
75	<66	66-73	>73	<71	71-78	>78
76	<66	66-74	>74	<71	71-79	>79
77	<66	66-74	>74	<71	71-79	>79
>77	<66	66-75	>75	<71	71-80	>80

* L_{dn} is used for land use where nighttime sensitivity is a factor; L_{eq} during the hour of maximum transit noise exposure is used for land use involving only daytime activities.

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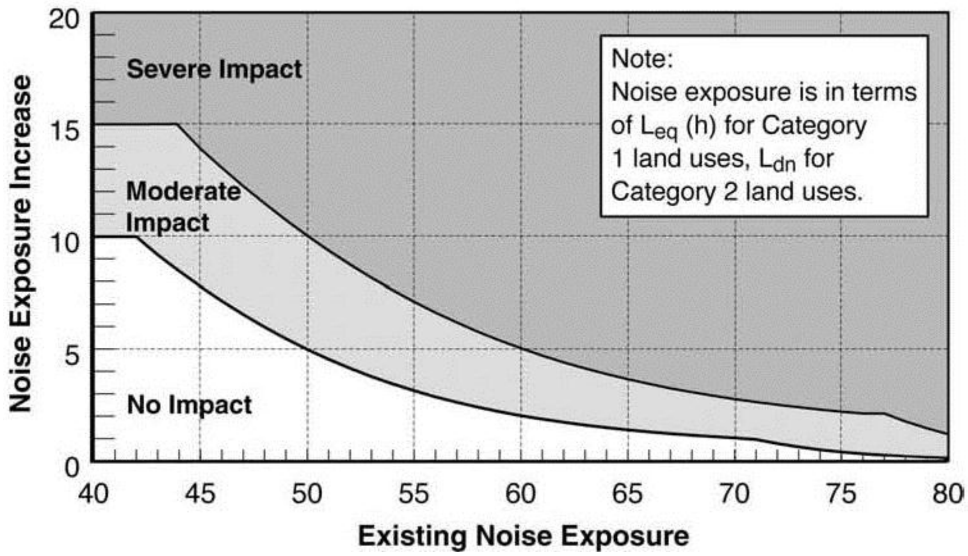
Exhibit 7-5 expresses these criteria in terms of the project-related increase in noise for Category 1 and 2 land uses.

Exhibit 7-5. Noise Impact Criteria for Rail Projects (source: FTA 2006)



Noise Impacts

Trucks

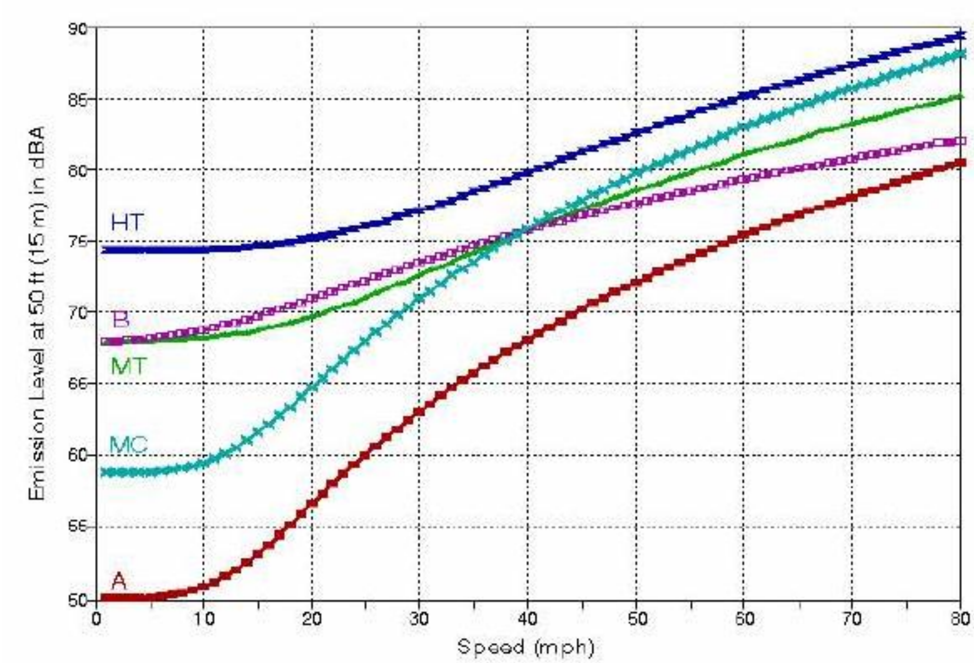
The FHWA Traffic Noise Model (TNM) is the primary tool used in the United States for assessing traffic noise. The model is based on vehicle noise emission levels gathered from over 6,000 vehicle passby events. The predominant sources of noise associated with a vehicle traveling on a road are tire/pavement noise and engine/exhaust noise. The tire/pavement component increases with vehicle speed while the engine/exhaust noise component is independent of vehicle speed. Tire/pavement noise is generated at ground level while engine/exhaust noise is generated above the ground at the engine height and at the exhaust stack height.

With regard to traffic noise analysis, FHWA defines trucks as follows:

> **Medium trucks:** all cargo vehicles with two axles and six tires. Generally, the gross vehicles weight is greater than 9,900 pounds but less than 26,400 pounds.
>
> **Heavy trucks:** all cargo vehicles with three or more axles. Generally the gross vehicles weight is greater than 26,400 pounds.

Exhibit 7-6 shows vehicle noise emission levels at 15 meters as function of speed for automobiles, motorcycles, medium trucks, buses, and heavy-duty trucks. These values are based on dense-graded asphaltic concrete (DGAC) and Portland cement concrete (PCC) pavements combined (referred to as "average" pavement in this TNM User's Guide), level-graded roadways, and constant-flow traffic.

Exhibit 7-6. Vehicle Noise Emission Levels from FHWA Traffic Noise Model (Source: FHWA 1998)



Note: A=autos, MC=motorcycles, MT=medium trucks, B=buses, HT=heavy trucks

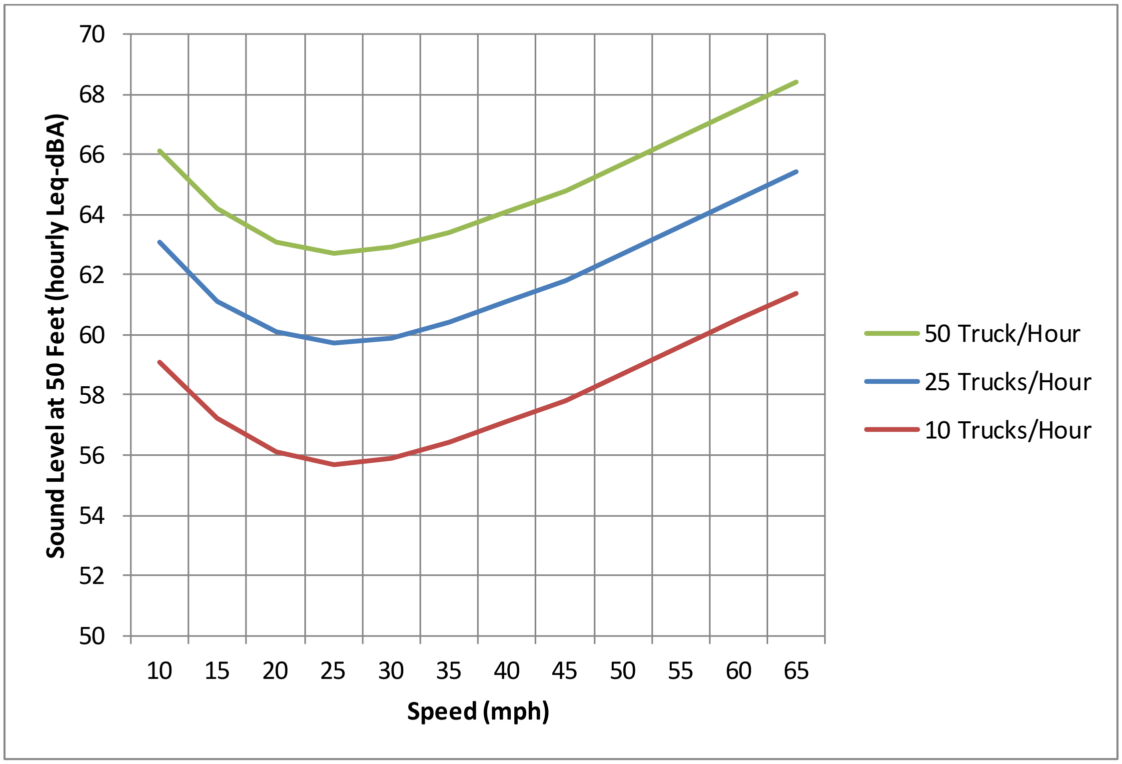
As would be expected and as illustrated in Exhibit 7-6, heavy trucks produce more sound than medium trucks and automobiles. Exhibit 7-7 equates noise from heavy trucks to medium trucks and autos in terms of equivalent vehicles. For example one heavy truck traveling at 35 mph produces a sound level equivalent to 19.1 automobiles. As speed increases, tire/pavement noise becomes predominant, which reduces the difference in noise level between trucks and automobiles. The sound produced by one truck traveling at 65 mph is equivalent to the sound of 8.9 automobiles.

Exhibit 7-7. Number of Equivalent Vehicles as a Function of Vehicle Type and Speed Based on TNM Noise Emission Levels (Caltrans 2009)

Speed (mph)	Equivalent Vehicles		
	1 Heavy Truck	1 Medium Truck	1 Auto
35	19.1	7.1	1
40	15.1	5.8	1
45	12.9	5.0	1
50	11.5	4.5	1
55	10.4	4.1	1
60	9.6	3.7	1
65	8.9	3.5	1
70	8.3	3.2	1

Exhibit 7-8 shows the noise level generated by heavy trucks traveling at various speeds. Noise levels were calculated using TNM Version 2.5.

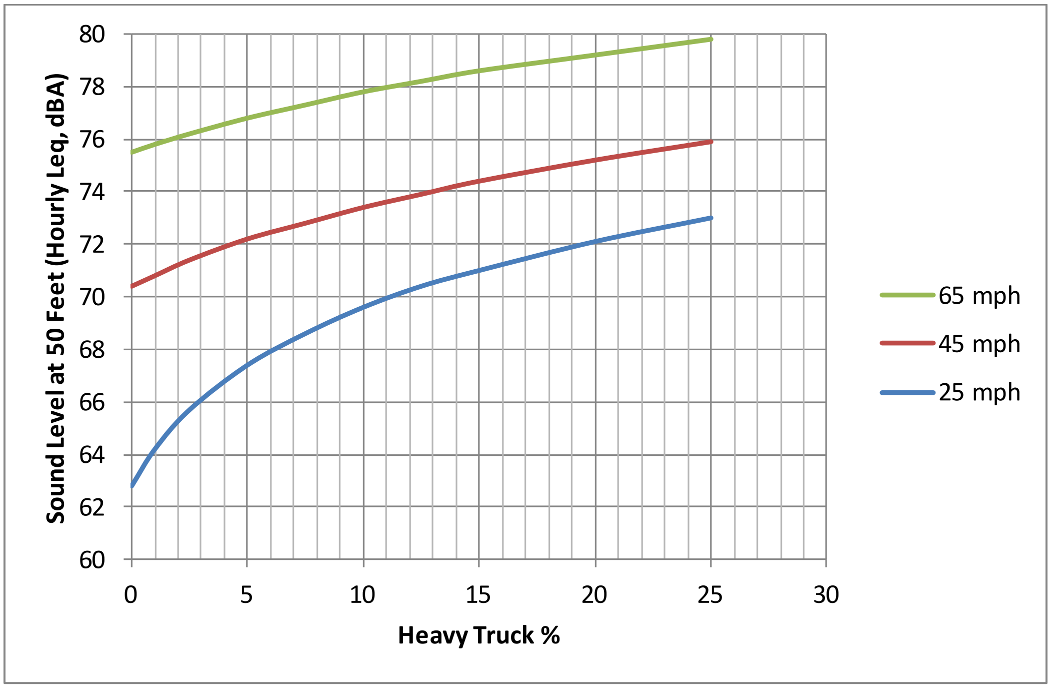
Exhibit 7-8. Truck Noise Levels as a Function of Speed



Vehicles traveling on a roadway are a line source. Assuming that absorptive ground such as grass is located between the roadway and a receiver, the rate of sound attenuation is about 4.5 dB per doubling of distance. For example Exhibit 7-8 indicates that the sound level of 50 trucks per hour traveling at 40 mph is 64 dBA at 50 feet. The sound level at 100 feet would be 59.5 dBA and the sound level at 200 feet would be 55 dBA.

Exhibit 7-9 shows how the percentage of heavy trucks influences overall traffic noise levels on a roadway with 2,000 vehicles per hour. Noise levels were calculated using TNM Version 2.5. As discussed above, the difference between the noise levels generated by automobiles and trucks is more pronounced at slower speeds. This is reflected in Exhibit 7-9, where the percentage of trucks has a greater influence on overall noise levels when traffic is traveling at slower speeds.

Exhibit 7-9. Effect of Heavy Truck Percentage on Traffic Noise Level



The extent to which truck movement can affect noise sensitive land uses is a function of many factors including:

1. The distance from the truck movement to the sensitive use, the number of trucks, and the speed of trucks.
2. The context – the effect of trucks is more pronounced in a quiet rural setting versus a noisy urban setting.
3. The time of day – people are more sensitive to noise during nighttime hours.

The data presented above indicates that there is potential for noise impacts to occur near truck routes.

Trains

The Federal Railroad Administration (FRA) relies upon the Federal Transit Administration (FTA) noise and vibration impact assessment procedures for assessing improvements to conventional passenger rail lines and stationary rail facilities and horn noise assessment. The procedures are provided in the FTA document entitled "Transit Noise and Vibration Impact Assessment" (FTA 2006). FRA has developed a supplemental freight rail analysis spreadsheet tool for the Chicago Rail Efficiency And Transportation Efficiency (CREATE) program, which is used to assess noise from freight rail and related stationary sources such as track crossovers, rail yards or shops, and layover tracks. Exhibit 7-10 summaries SEL values at 50 feet for sources related to freight rail.

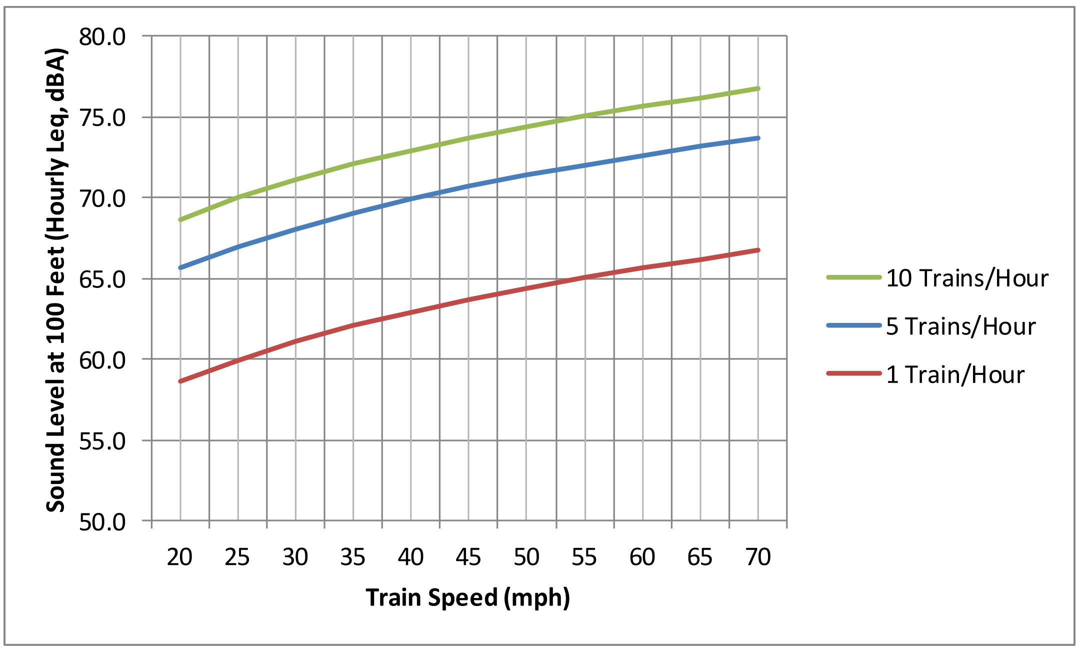
Exhibit 7-10: Typical Sound Exposure Levels for Freight Trains and Related Stationary Sources at 50 Feet (FRA 2006)

Noise Source	Sound Exposure Level (dBA) at 50 Feet
Freight locomotive	97
Freight cars*	100
Empty hopper cars*	104
Full hopper cars*	100
Track crossover	100
Rail yard or shop	118
Layover tracks	109

*based on 2,000 feet of cars.

Exhibit 7-11 shows the noise level at 100 feet from the track produced by a freight train with two locomotives and 2,000 feet of cars. Noise levels were calculated using the FRA CREATE train noise model.

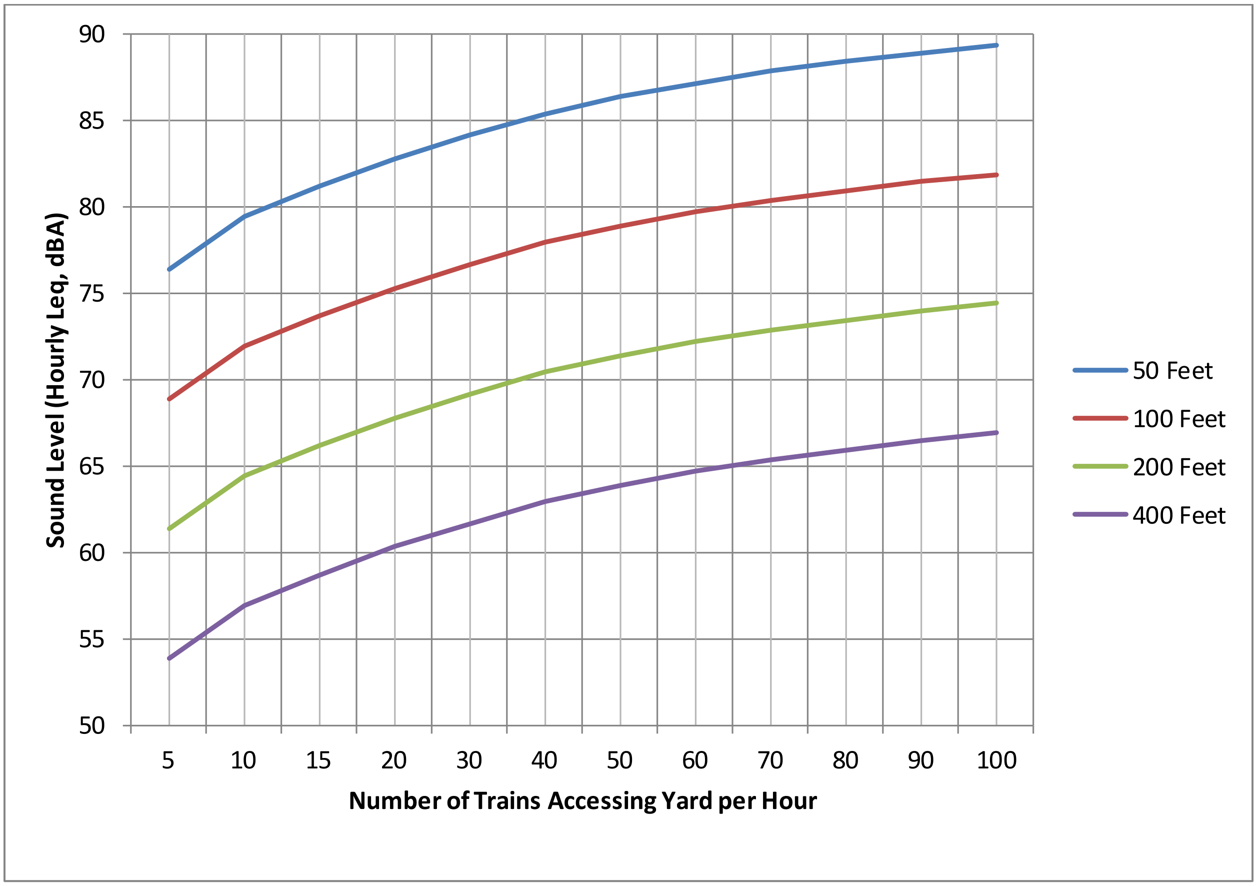
Exhibit 7-11. Freight Train Noise Levels (FRA 2006)



Similar to traffic on a highway, trains traveling on a track are considered to be a line source and sound attenuates at a rate of about 4.5 dB per doubling of distance.

Exhibit 7-12 shows the noise levels at various distances produced by an active freight train yard and shop area. Noise levels were calculated using the FRA CREATE train noise model. Activity in a freight train yard is considered to be a point source. The results in Exhibit 7-12 assume point source attenuation of 7.5 dB per doubling of distance.

Exhibit 7-12. Train Yard Noise Levels (FRA 2006)



Train horns are also a source of noise associated with trains. FRA has issued a Final Rule on the Use of Locomotive Horns at Highway-Rail Grade Crossings. This final rule, which requires that locomotive horns be sounded as a warning to highway users at public highway-rail crossings, took effect on June 24, 2005.

FRA has developed a source reference level for horn noise based on field measurements at grade crossings from many railroads. Rather than employing a single reference level, a reference level that varies along the railroad beginning at 1/4 mile (1320 feet) in advance and ending at the crossing was found to be more accurate. Field measurement data show an average Reference SEL of 107 dBA at 100 feet from the nearest track represents the horn noise in the distance from 1/4 mile to 1/8 mile from a crossing. Starting at the 1/8 mile point, the data show the horn is sounded more continuously, and more loudly, in the last part of the blowing sequence as the train reaches the crossing. Consequently, the SEL is assumed to increase linearly to 110 dBA at the roadways, as shown in Exhibit 7-13 (FRA 2011).

Exhibit 7-13. FRA Train Horn SEL Values as a Function of Distance (FRA 2011)

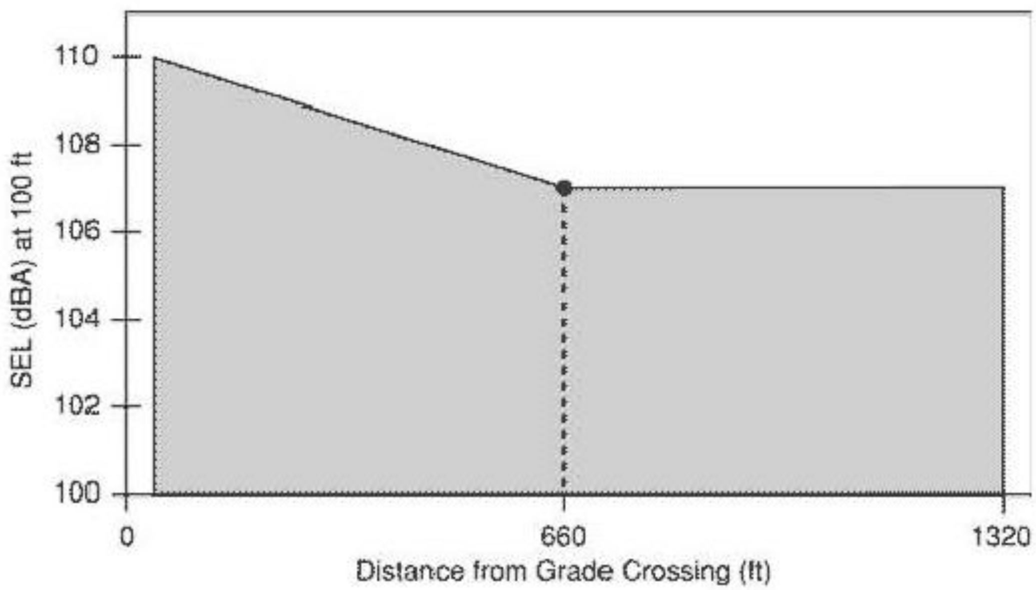
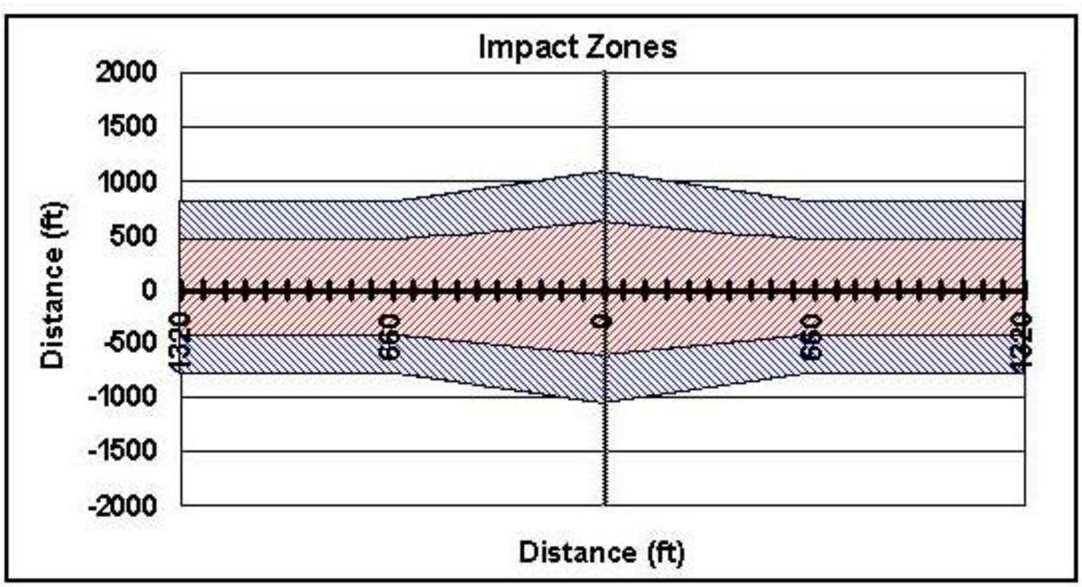


Exhibit 7-14 shows train horn noise levels in the vicinity of a typical suburban crossing. The outer line is a 65 Ldn contour resulting from horn operations.

Exhibit 7-14. Typical Suburban Train Horn Noise Levels (FTA 2011)



The extent to which trains and train yard activity can affect noise sensitive land uses is a function of many factors including:

1. The distance from the trains or yard to the sensitive use, the number of trains, and the speed of trains.
2. The context – the effect of trains is more pronounced in a quiet rural setting versus a noisy urban setting.

3. The time of day – people are more sensitive to noise during nighttime hours.

The data presented above indicates that there is potential for noise impacts to occur near train tracks and train yards.

Noise Mitigation Strategies

The following discussion presents mitigations that are commonly available to reduce noise from traffic and train operations. A key concept that applies to all noise impact situations is the source-path-receiver concept. The basic concept is that for noise to be an issue at a receiver there must be source of noise, a path for the noise to be transmitted, and a receiver to be affected.

Noise can be mitigated by treating any or all of these elements. For example noise from a truck can be reduced by placing a muffler on the exhaust thus reducing the noise at the source. The noise transmitted along a path between a source and a receiver can be reduced by blocking the path between the source and the receiver with a wall. The noise received at a receiver (such as inside a house) can be reduced by upgrading the acoustical insulation of the building shell.

Truck Noise Mitigation

The following are methods that can be used to reduce adverse noise affects associated with truck movement.

Source Mitigation

Exhaust Mufflers. Exhaust stack noise can be a predominant source of truck noise at high speeds. Trucks are typically provided with effective exhaust stack mufflers. However, over time the effectiveness of mufflers can degrade. Truck noise can be minimized by ensuring that trucks are equipped with fully functional exhaust muffling systems that are at least as affective original equipment.

Low noise pavement. Recent advances in pavement design have identified pavement types that reduce tire/pavement noise. Open grade asphalt concrete (OGAC) that has 15% to 25% voids has been shown to effective in reducing tire pavement noise with potential noise reductions relative to dense grade asphalt concrete (DGAC) in the range of 3 to 7 dB. A long-term study conducted along I-80 near Davis, CA by Caltrans indicates that OGAC pavement resulted in noise levels that were about 6 to 7 dBA below those measured for the baseline DGAC pavement. The OGAC has continued to maintain its acoustical characteristics and performance after a period of 10 years, with only a slight increase (~ 1½ dB) in noise levels over time (Caltrans 2010).

For trucks, the benefits of low noise pavements are more pronounced at higher speeds where the tire/pavement noise is much greater than at lower speeds. At lower speeds engine noise tends to be predominant. For noise modeling purposes, Caltrans recommends that adjustments for pavement only be applied where speeds are 55 mph or greater (Caltrans 2003).

Operational Restrictions. As shown in Exhibit 7-8, truck noise is directly related to speed. Reducing speed can reduce noise. For example, reducing speed from 45 mph to 25 mph would result in about a 2 dB reduction in noise. The number of trucks per day or per hour affects the hourly and daily cumulative sound levels. Limiting the number of trucks per hour or per day can reduce hourly and daily cumulative sound levels. Limiting trucking to daytime hours when people are less sensitive to noise does not reduce the noise produced by trucks but can be effective in reducing annoyance.

Engine Brakes. Truck drivers often use a compression release engine brake, frequently called a Jake brake or Jacobs brake, to slow down a truck. Use of this braking system creates a loud chattering sound that can be annoying to people located nearby. Restricting the use of engine brakes near noise sensitive uses can be effective in reducing annoyance from noise.

Path Mitigation

Noise Barriers. Placement of a barrier between a source and a receiver can be effective in reducing sound transmission. In general a barrier that breaks the line of sight between a source and a receiver will reduce noise by about 5 dB. As a barrier becomes higher the noise reduction increases with noise reductions potentially as high as 15 dB being achievable.

Receiver Mitigation

Building Shell Improvements. The noise received in the interior of a residence depends on the noise reduction provided by the building shell. The noise reduction provided by a building shell depends on many factors including the number of doors and windows, the wall construction, the number and size of openings (such as openings for ventilation). The noise reduction provided by a building shell can be improved by upgrading the windows to provide improved acoustical performance, ensuring that doors and windows when closed are well sealed with no air gaps, adding additional material to wall sections, and sealing vents.

Train Noise Mitigation

Exhibit 7-15 shows source, path, and receiver treatments that can be used to reduce train noise. Measures related to barriers and building shell improvements are similar to those described above for trucks.

Exhibit 7-15. Train Noise Mitigation Measures (FTA 2006)

Application	Mitigation Measure	Effectiveness
SOURCE	Stringent Vehicle & Equipment Noise Specifications	Varied
	Operational Restrictions	Varied
	Resilient or Damped Wheels*: For Rolling Noise on Tangent Track:	2 dB
	Resilient or Damped Wheels*: For Wheel Squeal on Curved Track:	10-20 dB
	Vehicle Skirts*	6-10 dB
	Undercar Absorption*	5 dB
	Spin-slide control (prevents flats)*	**
	Wheel Truing (eliminates wheel flats)*	**
	Rail Grinding (eliminates corrugations)*	**
	Turn Radii greater than 1000 ft*	(Avoids Squeal)
	Rail Lubrication on Sharp Curves*	(Reduces Squeal)
	Movable-Point Frogs (reduce rail gaps at crossovers)*	(Reduces Impact Noise)
	Engine Compartment Treatments (Buses)	6-10 dB
PATH	Sound Barriers close to Vehicles	6-15 dB
	Sound Barriers at ROW Line	3-10 dB
	Alteration of Horiz. & Vert. Alignments	Varied
	Acquisition of Buffer Zones	Varied
	Ballast on At-Grade Guideway*	3 dB
	Ballast on Aerial Guideway*	5 dB
	Resilient Track Support on Aerial Guideway	Varied
RECEIVER	Acquisition of Property Rights for Construction of Sound Barriers	5-10 dB
	Building Noise Insulation	5-20 dB

* Applies to rail projects only

** These mitigation measures work to maintain a rail system in its as-new condition. Without incorporating them into the system, noise levels could increase up to 10 dB.

The FRA final rule on train horns provides a process for localities nationwide to mitigate the effects of train horn noise by establishing new "quiet zones." Under this rule locomotive horn sounding is not required within highway-rail grade crossing corridors that are equipped with supplementary safety measures at each public highway-rail grade crossing. The final rule and details on this process are available on the FRA website at: http://www.fra.dot.gov/rpd/freight/1318.shtml.

References – Noise

Caltrans, Additional calibration of traffic noise prediction models, 2003.

Caltrans, *Technical Noise Supplement*, 2009, a technical supplement to the Protocol. Available at: http://www.dot.ca.gov/hq/env/noise/pub/tens_complete.pdf

Caltrans, I-80 Davis OGAC pavement noise study-traffic noise levels associated with aging open grade asphalt concrete overlay, 2010.

Federal Highway Administration, Traffic noise model user's guide, 1998.

Federal Railroad Administration, *High-Speed Ground Transportation Noise and Vibration Impact Assessment*, 2005. Available on FRA website: http://www.fra.dot.gov/downloads/RRDev/final_nv.pdf

Federal Railroad Administration, *CREATE Railroad Noise Model Use Guide*, 2006. Available at: http://www.fra.dot.gov/downloads/rrdev/020806%20CREATE%20noise%20model%20user%20guide.pdf

Federal Railroad Administration, Horn noise questions and answers, 2011. FRA website accessed October 21, 2011. http://www.fra.dot.gov/rpd/freight/1174.shtml

Federal Transit Administration, *Transit Noise and Vibration Impact Assessment,* 2006. Available at: http://www.fta.dot.gov/documents/FTA_Noise_and_Vibration_Manual.pdf

7.2. Vibration

Background

Ground vibration is an oscillatory motion of the soil particles with respect to the equilibrium position that can be described in terms of displacement, velocity, or acceleration. Vibration can be described by its peak and root mean square (r.m.s.) amplitudes. The r.m.s amplitude is useful for assessing human annoyance, while peak vibration is most often used for assessing the potential for damage to buildings structures.

Decibel notation is commonly used to describe vibration so as to cover the wide range of magnitudes that can be encountered. The vibration can be expressed in terms of the velocity level, in decibels, defined as:

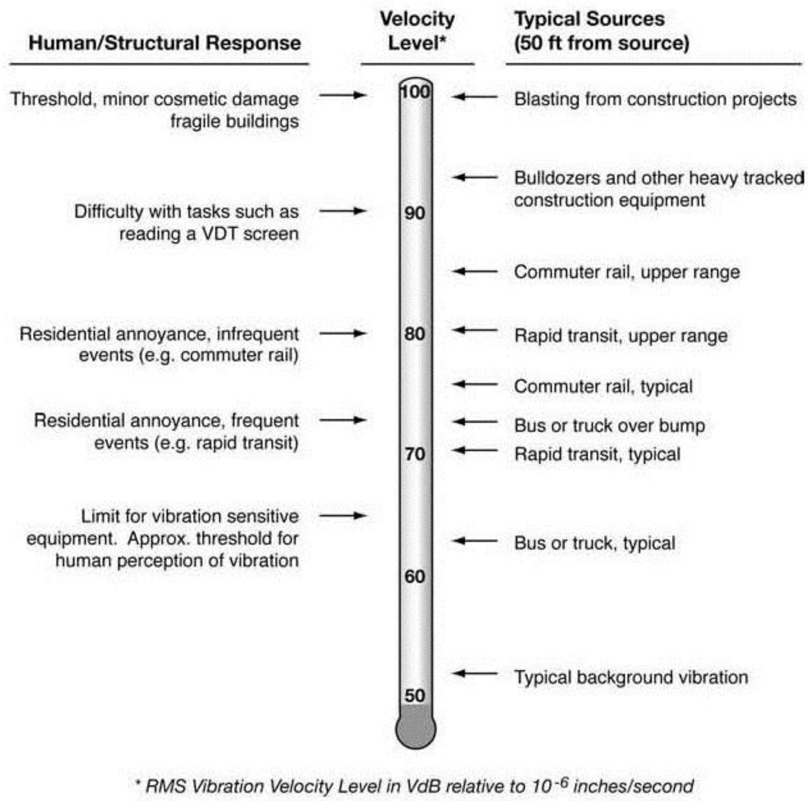
$$Lv = 20\log_{10}(v/v_{\text{ref}}),\ \text{VdB}$$

Where v = r.m.s velocity (in/sec) and Vref =1 micro-inch/sec

Vibration attenuates as a function of the distance between the source and the receiver due to geometric spreading and inherent damping in the soil that absorbs energy of the ground motion. Groundbome vibration from rail transport systems is caused by dynamic forces at the wheel/rail interface. It is influenced by many factors, which include the rail and wheel roughness, out-of-round wheel conditions, the mass and stiffness characteristics of the track support system, and the local soil conditions.

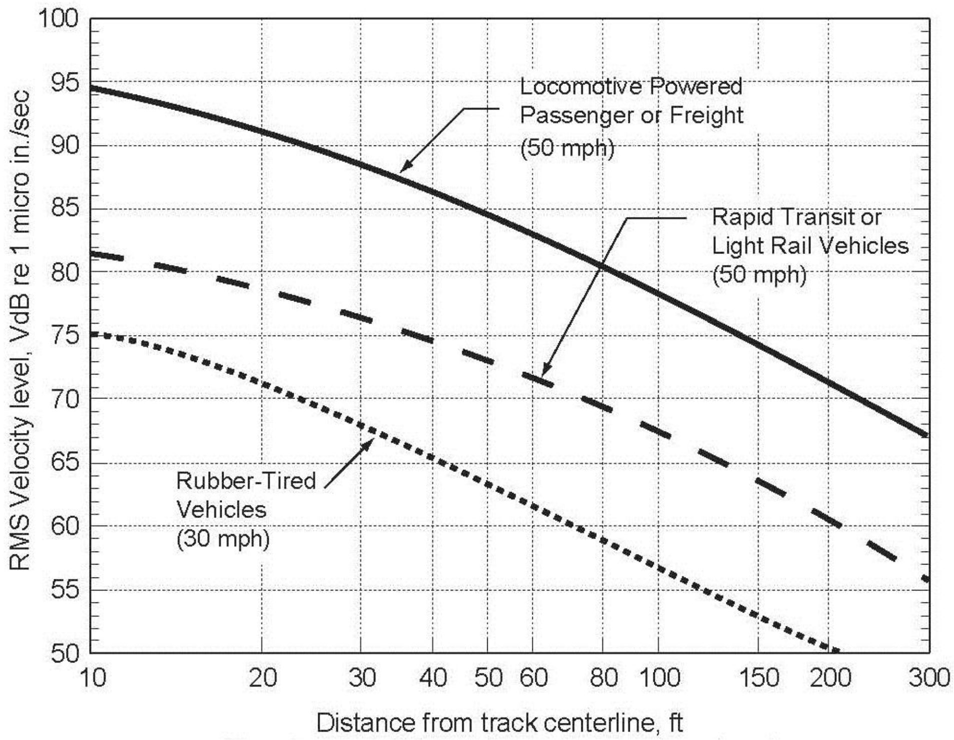
Exhibit 7-16 illustrates the typical levels of human and structural response to ground-borne vibration. The figure shows that the threshold of human perception is about 65 VdB, while the threshold for “cosmetic” structural damage is about 100 VdB. However, at the latter threshold, building damage is directly related to the condition of the structure. It is very rare that transportation-related ground vibration approaches building damage levels.

Exhibit 7-16. Typical Levels of Ground-Borne Vibration (source: FTA 2006)



Vibration generated by trains attenuates over distance similar to how sound attenuates with increasing distance from the source. Exhibit 7-17 shows how ground vibration generated by trains and vehicles typically attenuation with increasing distance from the track or roadway.

Exhibit 7-17. Generalized Ground Surface Vibration Curves (FTA 2006)



Vibration Impact Criteria

FTA has developed vibration impact criteria that relates to the sensitivity of the receiver, the level of vibration, and the number of vibration events per day. Exhibit 7-18 summarizes these vibration criteria.

Exhibit 7-18. Ground-Borne Vibration Impact Criteria (FTA 2006)

Land Use Category	GBV Impact Levels (VdB re 1 micro-inch/sec)		
	Frequent Events[1]	**Occasional Events**[2]	**Infrequent Events**[3]
Category 1: Buildings where vibration would interfere with interior operations	65 VdB	65 VdB	65 VdB
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB
Category 3: Institutional land uses with primary daytime use.	75 VdB	78 VdB	83 VdB

Notes:

1. "Frequent Events" is defined as more than 70 vibration events of the same source per day.
2. "Occasional Events" is defined as between 30 and 70 vibration events of the same source per day.
3. "Infrequent Events" is defined as fewer than 30 vibration events of the kind per day

Vibration Impacts

Trucks

Because trucks are supported on spring suspension and pneumatic tires, ground vibration is rarely an issue with truck movement. Exceptions to this occur when there is a significant discontinuity in the roadway surface. In this situation, a truck hitting the discontinuity can generate a ground vibration pulse that may be perceptible at nearby residences. Exhibit 7-17 shows generalized ground vibration levels produced by rubber-tired vehicles traveling at 30 mph on a smooth road.

Trains

Moving freight trains can be a significant source of ground vibration. Although trains are supported on spring suspension, the high axle loads and steel-to-steel contact between the wheels and rails can result in significant energy being imparted into the ground. The speed of the train and the condition of the wheels and track are significant factors in the ground vibration that is generated. Exhibit 7-17 shows generalized ground vibration levels produced by a locomotive powered freight train.

Exhibit 7-17 indicates that freight trains can cause ground vibration that exceeds the 75 VdB impact threshold for infrequent events (less than 70 events per day) for residences within about 150 feet of a track. The figure also indicates that threshold for frequent events (more than 70 per day) of 72 VdB can be exceeded within about 200 feet. Residences located within these distance could be subject to adverse vibration impacts.

Vibration Mitigation Strategies

The source-path-receiver concept discussed for noise also applies to ground vibration generated by trains. In this case the train is the source and the ground is the path. The following are methods that can be used to reduce adverse noise affects associated with train operations.

Source Mitigation

Maintenance. Degraded wheel and rail surfaces can cause vibration levels to increase by as much as 20 dB compared to new or well-maintained wheel and rail surfaces. Maintenance measures that can help reduce vibration include the following (FTA 2006):

- Rail grinding to smooth out corrugations in the rail surface that can develop over time. Rail grinding when truing can reduce vibration by as much as 10 dB.
- Wheel truing to re-contour the wheel to provide a smooth running surface and to remove wheel flats.
- Vehicle reconditioning programs to maintain the performance of the suspension system, brakes, and wheels.
- Wheel-flat detector systems that can identify when wheels are flat.

Special Track Support Systems. Special track systems such as floating slabs, resiliently supported ties, high-resilience fasteners, and ballast mast can be used to reduce groundborne vibration. Resiliently supported ties and ballast mats can reduce vibration by as much as 10 dB. A floating track slab can reduce noise by as much as 10 dB. High resilience fasteners can reduce vibration by as much as 5 dB (FTA 2006).

Path Mitigation

Trenches. The use of trenches located between the track and the receiver to control ground-borne vibration is analogous to the noise barrier for airborne noise described above. This type of system has not been used much in the U.S. but can be a practical method for controlling ground-borne vibration. To be effective the trench would need to be approximately 15 feet deep and can be either open or solid.

Receiver Mitigation

Building Modifications. In some circumstances it may be possible to modify a building to be less susceptible to ground vibration by supporting the building foundation on elastomeric pads. This is generally not an option for existing buildings but can be considered for new buildings.

References – Vibration

Caltrans, Transportation- and Construction-Induced Vibration Guidance Manual, 2004.

Federal Railroad Administration. High-speed ground transportation noise and vibration impact assessment, 2005.

Federal Transit Administration, Transit noise and vibration impact assessment, 2006.

7.3. Visual Impacts

Adverse Visual Impacts

A goods movement facility can have negative visual, or aesthetic, impacts if it degrades the existing scenic qualities or visual character of a site. This could happen, for example, if new infrastructure affects a scenic vista or blocks views of valued resources, such as trees, rock outcroppings, and historic buildings. These types of impacts are usually limited to rural areas or cases in which a new highway is being constructed. New railroad lines could have similar impacts; freight trains with double-stacked container cars can reach a height of up to 20 feet, which can reduce views of scenic vistas.

Goods movement terminals, such as a rail yard or distribution center, can have visual impacts because of stacking of containers on-site. Unlike ports and rail yards, which are limited to a select few locations, warehouses and distribution centers are scattered throughout Southern California, some in close proximity to residential areas. As a result, many communities may be affected by the visual impacts of these goods movement facilities.

Truck routes, rail yards, and other goods movement facilities could also have aesthetic impacts when they create substantial light or glare, which could adversely affect day or nighttime views in the area.

The degree of aesthetic impact depends on the characteristics of the scenic landscape enjoyed by the adjacent community before construction, and the change after construction. A freeway project might have little aesthetic impact if it is built level with the terrain with appropriate landscaping, or it could have significant aesthetic impact if it is built with elevated roadway or overpasses.

Visual Impact Mitigation Strategies

Strategies for mitigating visual impacts include controls on lighting, landscaping, and barrier walls.[67]

- **Spillover Lighting Controls.** Ambient levels of lighting from goods movement facilities can be intense, depending on the density of site development. Installation of new lighting structures can

[67] *Integrating Freight Facilities and Operations with Community Goals*, NCHRP Synthesis 320, Transportation Research Board, 2003.

change the ambient nighttime lighting levels. Spillover lighting can be reduced or eliminated by setting limits on allowable types or sizes of outdoor lighting, or specifying how the lighting should be shielded. Shielding specifications can specify the shape of shielding fixtures or the angle of lighting with respect to the ground. For new facilities, lighting specifications can be promoted through building codes and zoning ordinances. For existing facilities, incentives and outreach can help encourage facility owners to modify lighting.

- **Landscaping.** Adverse visual impacts of goods movement facilities can be mitigated using landscaping to block or soften aesthetic characteristics of the site. Landscaping can create a buffer zone between land uses, and allow goods movement facilities to better match the visual characteristics of surrounding regions. The selection of landscaping plants, shrubbery, or trees is often made with priorities given to indigenous species, fast-growing plants, and landscaping that requires less water and upkeep. Landscaping must be compatible with project site, and provisions must be made for landscaping maintenance.
- **Barrier walls.** In some cases, a barrier wall can help minimize negative visual impacts of goods movement facilities. Bordering walls serve to block visual impacts and can also reduce noise impacts. Effective barrier walls are often combined with landscaping, including tree planting.

The diversity of goods movement facilities and the communities in which they are located adds to the challenge of mitigating visual impacts. Mitigation strategies need to be adapted to the size and operation of each facility.

Appendices

Appendix A

This appendix contains details of the calculation of baseline truck emissions to 2035.

Exhibit A-1 shows factors used to adjust the EMFAC growth rates to account for the effects of the economic recession.

Exhibit A-1: Growth Adjustment Factors for Recession

Model Year	MHD Trucks	HHD Trucks		Model Year	MHD Trucks	HHD Trucks
2006	1.000000	1.000000		2015	0.867086	0.860130
2007	1.015334	0.993484		2016	0.879761	0.870912
2008	0.896484	0.865107		2017	0.891902	0.881656
2009	0.800732	0.777954		2018	0.891902	0.881656
2010	0.804783	0.794168		2019	0.891902	0.881656
2011	0.819155	0.812791		2020	0.891902	0.881656
2012	0.832869	0.828465		2021	0.891902	0.881656
2013	0.845942	0.841409		2022	0.891902	0.881656
2014	0.856907	0.851518		2023	0.891902	0.881656

The ARB Truck and Bus Rule requires that by 2023, all pre-2010 trucks with MHD and HHD Trucks be replaced with 2010+ model year trucks. The EMFAC model has been adjusted to reflect truck populations that exclude pre-2010 models by using ARBs estimates of the types of trucks purchased as replacements. Exhibits A-2 and A-3 show estimated truck populations by model year in the SCAB for calendar years 2023 and 2035.

Exhibit A-2: Revised Truck Populations for SCAB for 2023

Model Year	MHD Trucks	HHD Trucks
2023	6,994	4,679
2022	7,177	4,431
2021	6,889	3,846
2020	6,718	3,675
2019	6,510	3,678
2018	6,381	3,694
2017	7,720	3,798
2016	6,677	3,565
2015	7,236	4,088
2014	5,351	3,293
2013	4,531	2,859
2012	4,024	3,644
2011	3,631	2,044
2010	3,594	1,914
Total	83,434	49,207

Exhibit A-3: Revised Truck Populations for SCAB for 2035

Model Year	T6 Trucks	T7 Trucks
2035	5,886	4,758
2034	5,794	4,641
2033	5,718	4,401
2032	5,642	4,223
2031	5,579	4,038
2030	5,571	3,962
2029	5,410	3,853
2028	5,155	3,738
2027	4,941	3,631
2026	4,712	3,519
2025	4,495	3,426
2024	4,312	3,249
2023	5,034	3,354
2022	4,659	3,068
2021	4,410	2,739
2020	4,211	2,370
2019	3,815	2,207
2018	3,415	2,017
2017	3,551	1,838
2016	3,170	1,650
2015	3,314	1,582
2014	2,625	1,199
2013	2,171	946
2012	1,923	990
2011	1,681	566
2010	1,581	461
Total	108,775	72,425

Exhibits A-4 and A-5 show estimated truck populations by model year in the SCAG region for calendar years 2023 and 2035.

Exhibit A-4: Revised Truck Populations for SCAG Area Counties for 2023

Model Year	Imperial		Los Angeles		Orange		Riverside		San Bernardino		Ventura	
	MHD	HHD	MHD	HHD	MHD	HHD	MHD	HHD	MHD	HHD	MHD	HHD
2023	141	676	4,019	2,451	1,487	529	801	2,594	1,090	2,928	346	143
2022	142	650	4,127	2,363	1,531	481	826	2,459	1,112	2,745	355	131

2021	135	586	3,963	2,107	1,475	404	798	2,163	1,075	2,307	329	111
2020	135	583	3,733	2,047	1,505	379	832	2,050	1,081	2,161	305	105
2019	132	588	3,629	2,053	1,453	381	803	2,049	1,045	2,157	295	105
2018	131	591	3,572	2,064	1,420	382	783	2,049	1,016	2,163	291	105
2017	152	600	4,350	2,133	1,709	393	937	2,094	1,210	2,219	376	111
2016	133	516	3,820	2,011	1,448	383	792	1,939	1,040	2,045	342	110
2015	131	528	4,180	2,392	1,579	452	808	2,094	1,111	2,358	373	129
2014	97	428	3,061	1,916	1,180	363	610	1,744	838	1,922	274	105
2013	83	375	2,562	1,655	997	313	562	1,517	705	1,661	232	92
2012	70	478	2,265	2,111	871	393	513	1,907	651	2,116	205	120
2011	60	276	1,991	1,180	767	221	501	1,082	637	1,187	185	76
2010	56	261	1,915	1,110	772	205	519	1,009	661	1,112	195	71
Total	1,598	7,136	47,189	27,593	18,194	5,279	10,087	26,748	13,274	29,081	4,104	1,514

Exhibit A-5: Revised Truck Populations for SCAG Area Counties for 2035

Model Year	Imperial		Los Angeles		Orange		Riverside		San Bernardino		Ventura	
	MHD	HHD	MHD	HHD	MHD	HHD	MHD	HHD	MHD	HHD	MHD	HHD
2035	157	806	3,801	1,953	1,126	548	446	3,127	841	3,444	271	173
2034	154	775	3,730	1,934	1,120	536	446	3,029	825	3,334	267	170
2033	147	735	3,646	1,858	1,098	510	488	2,844	810	3,150	263	161
2032	142	707	3,536	1,835	1,084	497	529	2,698	814	3,051	256	156
2031	135	686	3,412	1,797	1,040	473	571	2,543	885	2,952	251	142
2030	131	665	3,257	1,916	1,075	431	618	2,396	968	2,756	238	130
2029	125	642	3,155	1,874	1,051	419	602	2,326	940	2,673	233	127
2028	118	618	3,012	1,826	997	408	573	2,248	893	2,585	221	123
2027	111	592	2,892	1,783	956	397	550	2,166	850	2,497	214	120
2026	106	569	2,758	1,737	916	386	524	2,088	803	2,409	206	115
2025	101	548	2,628	1,970	878	377	500	2,018	765	2,330	198	112
2024	96	514	2,527	1,616	843	358	476	1,898	724	2,191	191	106
2023	105	505	2,903	1,674	1,071	388	560	1,921	788	2,150	250	104
2022	97	469	2,688	1,577	993	335	521	1,755	724	1,937	231	91
2021	89	432	2,545	1,472	946	287	498	1,580	691	1,651	210	79
2020	87	393	2,331	1,300	955	243	515	1,354	685	1,394	188	68
2019	80	369	2,119	1,214	861	227	464	1,258	619	1,294	170	63
2018	73	338	1,905	1,111	768	207	414	1,144	550	1,180	153	57
2017	74	304	1,991	1,018	795	189	427	1,036	564	1,072	173	54
2016	66	243	1,816	922	690	177	369	910	498	942	165	51
2015	61	204	1,920	923	728	177	356	813	511	908	173	51
2014	48	156	1,504	696	584	133	290	640	413	698	135	39
2013	40	124	1,228	546	482	104	265	506	339	548	112	31
2012	34	130	1,083	571	419	107	241	523	313	573	99	34
2011	28	76	922	326	357	61	229	301	297	328	86	22
2010	24	63	839	267	342	50	227	244	295	267	87	17
Total	2,431	11,663	64,147	35,715	22,172	8,025	11,698	43,364	17,403	48,314	5,037	2,397

Exhibits A-6 through A-11 shows 2023 truck emissions by county.

Exhibit A-6: Truck Emissions for Imperial County in 2023

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	1,943	75,000	0.125	0.001	-	0.002	0.001	0.002	0.003
	Diesel	579	21,000	0.049	0.001	-	0.001	0.001	-	0.001
	All	2,522	96,000	0.174	0.002	-	0.003	0.002	0.002	0.004
LHD2	Gasoline	787	30,000	0.051	-	-	0.001	0.001	-	0.001
	Diesel	604	22,000	0.040	0.001	-	0.001	0.001	-	0.001
	All	1,391	52,000	0.091	0.001	-	0.002	0.002	-	0.002
MHD	Gasoline	486	21,000	0.051	-	-	-	-	-	0.001
	Diesel	1,598	106,000	0.109	0.009	0.001	0.010	0.010	0.002	0.013
	All	2,084	127,000	0.160	0.009	0.001	0.010	0.010	0.002	0.014
HHD	Gasoline	128	15,000	0.107	-	-	0.001	-	-	0.001
	Diesel	7,136	1,557,000	5.489	0.150	0.036	0.187	0.164	0.110	0.274
	All	7,264	1,572,000	5.596	0.150	0.036	0.188	0.164	0.110	0.275

T&B = Tire and Brake emissions

Exhibit A-7: Truck Emissions for Los Angeles County in 2023

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	89,448	4,216,000	6.889	0.054	0.039	0.093	0.058	0.114	0.172
	Diesel	19,805	958,000	2.372	0.024	0.009	0.033	0.026	0.026	0.052
	All	109,253	5,174,000	9.261	0.078	0.048	0.126	0.084	0.140	0.224
LHD2	Gasoline	19,351	913,000	1.326	0.011	0.008	0.020	0.012	0.025	0.037
	Diesel	14,028	660,000	1.727	0.017	0.006	0.023	0.019	0.018	0.037
	All	33,379	1,573,000	3.053	0.028	0.014	0.043	0.031	0.043	0.074
MHD	Gasoline	13,607	695,000	1.324	0.010	0.006	0.016	0.011	0.019	0.030
	Diesel	47,189	3,699,000	4.541	0.359	0.034	0.393	0.390	0.100	0.490
	All	60,796	4,394,000	5.865	0.369	0.040	0.409	0.401	0.119	0.520
HHD	Gasoline	1,168	91,000	1.069	0.002	0.001	0.003	0.002	0.004	0.006
	Diesel	27,683	7,620,000	26.735	0.853	0.178	1.031	0.928	0.539	1.467
	All	28,851	7,711,000	27.804	0.855	0.179	1.034	0.930	0.543	1.473

T&B = Tire and Brake emissions

Exhibit A-8: Truck Emissions for Orange County in 2023

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	37,277	1,507,000	2.397	0.016	0.014	0.030	0.018	0.041	0.058
	Diesel	9,008	364,000	0.950	0.009	0.003	0.012	0.009	0.010	0.019
	All	46,285	1,871,000	3.347	0.025	0.017	0.042	0.027	0.051	0.077
LHD2	Gasoline	7,504	302,000	0.448	0.003	0.003	0.006	0.003	0.008	0.011
	Diesel	5,607	223,000	0.582	0.005	0.002	0.007	0.006	0.006	0.012
	All	13,111	525,000	1.030	0.008	0.005	0.013	0.009	0.014	0.023
MHD	Gasoline	5,180	227,000	0.408	0.003	0.002	0.005	0.003	0.006	0.009
	Diesel	18,174	1,214,000	1.373	0.100	0.011	0.111	0.109	0.033	0.142
	All	23,354	1,441,000	1.781	0.103	0.013	0.116	0.112	0.039	0.151
HHD	Gasoline	328	18,000	0.252	-	-	0.001	-	0.001	0.001
	Diesel	5,279	1,244,000	4.083	0.123	0.029	0.152	0.134	0.088	0.222
	All	5,607	1,262,000	4.335	0.123	0.029	0.153	0.134	0.089	0.223

T&B = Tire and Brake emissions

Exhibit A-9: Truck Emissions for Riverside County in 2023

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	29,986	1,186,000	1.661	0.012	0.011	0.023	0.013	0.032	0.045
	Diesel	7,730	299,000	0.757	0.007	0.003	0.010	0.007	0.008	0.015
	All	37,716	1,485,000	2.418	0.019	0.014	0.033	0.020	0.040	0.060
LHD2	Gasoline	6,142	240,000	0.341	0.002	0.002	0.004	0.002	0.006	0.009
	Diesel	5,066	190,000	0.537	0.004	0.002	0.006	0.005	0.006	0.010
	All	11,208	430,000	0.878	0.006	0.004	0.010	0.007	0.012	0.019
MHD	Gasoline	2,838	142,000	0.221	0.002	0.001	0.003	0.002	0.004	0.006
	Diesel	10,087	750,000	0.891	0.067	0.006	0.074	0.073	0.020	0.093
	All	12,925	892,000	1.112	0.069	0.007	0.077	0.075	0.024	0.099
HHD	Gasoline	565	68,000	0.485	0.001	0.001	0.002	0.001	0.003	0.004
	Diesel	26,748	6,042,000	19.466	0.575	0.141	0.715	0.625	0.428	1.052
	All	27,313	6,110,000	19.951	0.576	0.142	0.717	0.626	0.431	1.056

T&B = Tire and Brake emissions

Exhibit A-10: Truck Emissions for San Bernardino County in 2023

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	31,233	1,352,000	1.940	0.013	0.012	0.025	0.014	0.037	0.051
	Diesel	7,971	338,000	0.933	0.008	0.003	0.011	0.008	0.009	0.018
	All	39,204	1,690,000	2.873	0.021	0.015	0.036	0.022	0.046	0.069
LHD2	Gasoline	6,996	299,000	0.407	0.003	0.003	0.005	0.003	0.008	0.011
	Diesel	5,631	233,000	0.651	0.005	0.002	0.007	0.006	0.006	0.012
	All	12,627	532,000	1.058	0.008	0.005	0.012	0.009	0.014	0.023
MHD	Gasoline	3,606	185,000	0.252	0.002	0.002	0.004	0.002	0.005	0.007
	Diesel	13,274	988,000	1.261	0.084	0.009	0.093	0.091	0.027	0.118
	All	16,880	1,173,000	1.513	0.086	0.011	0.097	0.093	0.032	0.125
HHD	Gasoline	586	82,000	0.622	0.001	0.001	0.003	0.001	0.004	0.005
	Diesel	29,081	6,799,000	21.777	0.768	0.158	0.926	0.835	0.482	1.317
	All	29,667	6,881,000	22.399	0.769	0.159	0.929	0.836	0.486	1.322

T&B = Tire and Brake emissions

Exhibit A-11: Truck Emissions for Ventura County in 2023

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	11,953	531,000	0.784	0.005	0.005	0.010	0.006	0.014	0.020
	Diesel	2,931	129,000	0.329	0.003	0.001	0.004	0.003	0.004	0.007
	All	14,884	660,000	1.113	0.008	0.006	0.014	0.009	0.018	0.027
LHD2	Gasoline	2,386	105,000	0.153	0.001	0.001	0.002	0.001	0.002	0.004
	Diesel	1,901	81,000	0.232	0.002	-	0.003	0.002	0.002	0.004
	All	4,287	186,000	0.385	0.003	0.001	0.005	0.003	0.004	0.008
MHD	Gasoline	1,263	48,000	0.112	0.001	-	0.001	0.001	0.002	0.002
	Diesel	4,104	250,000	0.292	0.018	0.002	0.021	0.020	0.006	0.027
	All	5,367	298,000	0.404	0.019	0.002	0.022	0.021	0.008	0.029
HHD	Gasoline	91	5,000	0.064	-	-	-	-	-	-
	Diesel	1,514	385,000	1.288	0.042	0.009	0.051	0.046	0.027	0.073
	All	1,605	390,000	1.352	0.042	0.009	0.051	0.046	0.027	0.073

T&B = Tire and Brake emissions

Exhibits A-12 through A-17 shows 2035 truck emissions by county.

Exhibit A-12: Emissions for Imperial County in 2035

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	2,761	105,000	0.150	0.002	0.001	0.003	0.002	0.002	0.005
	Diesel	681	25,000	0.029	0.001	-	0.001	0.001	-	0.001
	All	3,442	130,000	0.179	0.003	0.001	0.004	0.003	0.002	0.006
LHD2	Gasoline	1,094	41,000	0.055	0.001	-	0.001	0.001	0.002	0.002
	Diesel	804	30,000	0.028	0.001	-	0.001	0.001	-	0.002
	All	1,898	71,000	0.083	0.002	-	0.002	0.002	0.002	0.004
MHD	Gasoline	647	29,000	0.035	-	-	0.001	-	-	0.001
	Diesel	2,431	136,000	0.153	0.015	0.001	0.016	0.016	0.004	0.020
	All	3,078	165,000	0.188	0.015	0.001	0.017	0.016	0.004	0.021
HHD	Gasoline	179	22,000	0.137	-	-	0.001	-	0.001	0.001
	Diesel	11,663	2,135,000	8.927	0.262	0.049	0.311	0.285	0.151	0.436
	All	11,842	2,157,000	9.064	0.262	0.049	0.312	0.285	0.152	0.437

T&B = Tire and Brake emission

Exhibit A-13: Emissions for Los Angeles County in 2035

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	109,725	5,221,000	6.236	0.064	0.048	0.112	0.069	0.141	0.211
	Diesel	25,194	1,199,000	1.697	0.025	0.011	0.036	0.027	0.033	0.059
	All	134,919	6,420,000	7.933	0.089	0.059	0.148	0.096	0.174	0.270
LHD2	Gasoline	23,869	1,134,000	1.189	0.013	0.011	0.024	0.014	0.031	0.045
	Diesel	17,432	822,000	1.102	0.016	0.008	0.023	0.017	0.022	0.039
	All	41,301	1,956,000	2.291	0.029	0.019	0.047	0.031	0.053	0.084
MHD	Gasoline	16,893	872,000	0.889	0.012	0.008	0.020	0.013	0.024	0.037
	Diesel	64,147	4,176,000	5.822	0.499	0.039	0.537	0.542	0.113	0.655
	All	81,040	5,048,000	6.711	0.511	0.047	0.557	0.555	0.137	0.692
HHD	Gasoline	777	77,000	0.617	0.002	0.001	0.003	0.002	0.003	0.005
	Diesel	35,442	7,860,000	31.491	0.979	0.183	1.162	1.065	0.557	1.621
	All	36,219	7,937,000	32.108	0.981	0.184	1.165	1.067	0.560	1.626

T&B = Tire and Brake emissions

Exhibit A-14: Emissions for Orange County in 2035

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	41,939	1,672,000	2.220	0.018	0.016	0.034	0.020	0.045	0.065
	Diesel	9,853	389,000	0.570	0.008	0.003	0.011	0.008	0.010	0.019
	All	51,792	2,061,000	2.790	0.026	0.019	0.045	0.028	0.055	0.084
LHD2	Gasoline	8,451	337,000	0.398	0.003	0.003	0.007	0.004	0.009	0.013
	Diesel	6,226	246,000	0.324	0.004	0.002	0.007	0.005	0.006	0.011
	All	14,677	583,000	0.722	0.007	0.005	0.014	0.009	0.015	0.024
MHD	Gasoline	5,776	246,000	0.272	0.003	0.002	0.005	0.003	0.006	0.010
	Diesel	22,172	1,191,000	1.516	0.127	0.011	0.138	0.138	0.032	0.170
	All	27,948	1,437,000	1.788	0.130	0.013	0.143	0.141	0.038	0.180
HHD	Gasoline	203	16,000	0.131	-	-	0.001	-	0.001	0.001
	Diesel	8,025	1,600,000	5.786	0.166	0.037	0.204	0.181	0.113	0.294
	All	8,228	1,616,000	5.917	0.166	0.037	0.205	0.181	0.114	0.295

T&B = Tire and Brake emissions

Exhibit A-15: Emissions for Riverside County in 2035

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	33,235	1,250,000	1.633	0.015	0.011	0.026	0.016	0.034	0.050
	Diesel	7,952	294,000	0.435	0.006	0.003	0.009	0.006	0.008	0.014
	All	41,187	1,544,000	2.068	0.021	0.014	0.035	0.022	0.042	0.064
LHD2	Gasoline	6,913	259,000	0.318	0.003	0.003	0.005	0.003	0.007	0.010
	Diesel	5,200	191,000	0.270	0.004	0.002	0.005	0.004	0.006	0.009
	All	12,113	450,000	0.588	0.007	0.005	0.010	0.007	0.013	0.019
MHD	Gasoline	3,056	142,000	0.146	0.002	0.001	0.003	0.002	0.004	0.006
	Diesel	11,698	690,000	0.925	0.084	0.006	0.091	0.092	0.019	0.110
	All	14,754	832,000	1.071	0.086	0.007	0.094	0.094	0.023	0.116
HHD	Gasoline	703	94,000	0.560	0.002	0.001	0.003	0.002	0.004	0.006
	Diesel	43,364	8,324,000	29.849	0.809	0.194	1.003	0.880	0.589	1.469
	All	44,067	8,418,000	30.409	0.811	0.195	1.006	0.882	0.593	1.475

T&B = Tire and Brake emissions

Exhibit A-16: Emissions for San Bernardino County in 2035

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	38,532	1,629,000	2.011	0.015	0.015	0.031	0.017	0.045	0.061
	Diesel	9,154	382,000	0.635	0.007	0.003	0.010	0.008	0.010	0.018
	All	47,686	2,011,000	2.646	0.022	0.018	0.041	0.025	0.055	0.079
LHD2	Gasoline	8,701	362,000	0.410	0.003	0.003	0.007	0.003	0.010	0.013
	Diesel	6,478	266,000	0.407	0.004	0.003	0.007	0.005	0.008	0.012
	All	15,179	628,000	0.817	0.007	0.006	0.014	0.008	0.018	0.025
MHD	Gasoline	4,513	219,000	0.206	0.003	0.002	0.005	0.003	0.006	0.009
	Diesel	17,403	1,053,000	1.679	0.109	0.009	0.119	0.119	0.029	0.147
	All	21,916	1,272,000	1.885	0.112	0.011	0.124	0.122	0.035	0.156
HHD	Gasoline	768	121,000	0.816	0.002	0.002	0.004	0.002	0.006	0.007
	Diesel	48,314	9,704,000	34.041	1.218	0.225	1.443	1.324	0.687	2.011
	All	49,082	9,825,000	34.857	1.220	0.227	1.447	1.326	0.693	2.018

T&B = Tire and Brake emissions

Exhibit A-17: Emissions for Ventura County in 2035

Vehicle Class	Fuel Type	Population	VMT	Tons per day						
					PM2.5			PM10		
				NOx	Exhaust	T&B	Total	Exhaust	T&B	Total
LHD1	Gasoline	13,486	590,000	0.739	0.007	0.005	0.012	0.007	0.016	0.023
	Diesel	3,184	138,000	0.203	0.003	0.001	0.004	0.003	0.004	0.007
	All	16,670	728,000	0.942	0.010	0.006	0.016	0.010	0.020	0.030
LHD2	Gasoline	2,732	120,000	0.136	0.001	0.001	0.002	0.001	0.004	0.005
	Diesel	2,040	88,000	0.124	0.002	0.001	0.002	0.002	0.002	0.004
	All	4,772	208,000	0.260	0.003	0.002	0.004	0.003	0.006	0.009
MHD	Gasoline	1,345	52,000	0.068	0.001	-	0.001	0.001	0.002	0.002
	Diesel	5,037	250,000	0.320	0.024	0.002	0.027	0.026	0.006	0.033
	All	6,382	302,000	0.388	0.025	0.002	0.028	0.027	0.008	0.035
HHD	Gasoline	60	5,000	0.036	-	-	-	-	-	-
	Diesel	2,396	528,000	1.922	0.058	0.012	0.070	0.063	0.037	0.100
	All	2,456	533,000	1.958	0.058	0.012	0.070	0.063	0.037	0.100

T&B = Tire and Brake emissions

Appendix B

This appendix contains truck emission factors used to analyze operational strategies in Section 6.

Exhibit B-1. HHDV Truck Emission Factors for 2010, South Coast Air Basin

Speed (mph)	NOx	CO2	PM2.5*	PM10*
idle	40.987	3,845.36	2.577	2.842
5	28.188	3,165.45	1.755	1.949
10	20.337	2,595.96	1.154	1.296
15	17.389	2,183.16	0.81	0.922
20	16.641	2,042.69	0.683	0.784
25	16.05	1,924.23	0.588	0.681
30	15.615	1,827.81	0.526	0.613
35	15.336	1,753.41	0.497	0.581
40	15.214	1,701.03	0.5	0.585
45	15.248	1,670.68	0.536	0.624
50	15.438	1,662.35	0.604	0.698
55	15.785	1,676.05	0.705	0.808
60	16.288	1,711.77	0.839	0.953
65	40.987	3,845.36	2.577	2.842

Exhibit B-2. 2023 Idle Emission Factors, South Coast Air Basin (grams/hour)

Vehicle Type	NOx	PM2.5	PM10	CO2
LHDT1	15.41	0.138	0.150	4647
LHDT2	32.67	0.321	0.349	4488
MHDT	63.42	0.622	0.676	4205
HHDT	122.04	0.100	0.109	6538

Exhibit B-3. 2035 Idle Emission Factors, South Coast Air Basin (grams/hour)

Vehicle Type	NOx	PM2.5	PM10	CO2
LHDT1	15.26	0.137	0.149	4649
LHDT2	32.44	0.310	0.337	4491
MHDT	62.37	0.612	0.665	4215
HHDT	122.29	0.101	0.110	6551