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Evaluation of the Air Quality and Greenhouse Gas Benefits of an Advanced Low-NOx Compressed Natural Gas (CNG) Engine in Medium and Heavy-Duty Vehicles in California

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Evaluation of the Air Quality and Greenhouse Gas Benefits of an Advanced Low-NO_x Compressed Natural Gas (CNG) Engine in Medium and Heavy-Duty Vehicles in California

A Research Report from the University of California Institute of Transportation Studies

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16. Abstract

The goal of this research is to assess the greenhouse gas (GHG) emissions and air quality (AQ) impacts of transitions to advanced low-NOx Compressed Natural Gas (CNG) engines in medium-duty vehicle (MDV) and heavy-duty vehicle (HDV) applications in California with a particular emphasis on renewable natural gas (RNG) as a fueling pathway. To evaluate regional AQ impacts in 2035, pollutant emissions from all end-use sectors are projected from current levels and spatially and temporally resolved. Scenarios are constructed beginning with both a conservative (Base Case) and more optimistic (SIP) case regarding advanced vehicle technology and fuels integration to provide spanning of potential impacts. To capture the impact of seasonal dynamics on pollutant formation and fate, two modeling periods are conducted including a winter and summer episode. To estimate the potential GHG impacts of transitions to advanced CNG engines in HDV and MDV, scenarios are evaluated under various assumptions regarding fuel pathways to meet CNG demand from a life cycle perspective. Scenarios are compared to the baseline cases assuming (1) all CNG is provided from conventional fossil natural gas and (2) under a range of possible resource availabilities associated with RNG and renewable synthetic natural gas (RSNG) from in-state resources. Key findings include: i) expanding the deployment of advanced CNG MDV and HDV can reduce summer ground-level ozone concentrations and ground-level $PM_{2.5}$ in key regions of California; ii) the largest AQ benefits are associated with reducing emissions from HDV; iii) in-state RNG pathways can meet the CNG demand estimated for both baseline cases; iv) in-state resources are unable to entirely meet CNG demand for the high total CNG demand estimated for the majority of Base alternative cases, and v) advanced CNG HDV and MDV can moderately reduce GHG emissions if fossil natural gas is used (14 to 26%).

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Disclaimer

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June 2017

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Executive Summary

Introduction

As a fundamental part of California's on-road goods movement sector, medium (MDV) and heavy-duty (HDV) vehicles provide important services to California's economy. However, emissions from MDV and HDV current represent a significant source of pollution within the State impacting regional air quality (AQ) with ensuing harmful health impacts to California citizens. Additionally, MDV and HDV emissions of greenhouse gasses (GHG) must be reduced to achieve State climate goals established under AB 32 [1]. Therefore, transitions from the current model of vehicles powered by combustion engines using petroleum fuels to cleaner, lower emitting technologies and fuels must be undertaken to ensure environmental quality goals are met.

A prominent near-zero technology for application in both the MDV and HDV sectors is the low-NO_x compressed natural gas (herein referred to as the "advanced CNG") engine developed by Cummins- Westport [2]. Advanced CNG engines have been certified in some size classes to reduce oxides of nitrogen (NO_x) emissions to levels considered near-zero, i.e., 90% below the existing California NO_X standard for on-road heavy-duty engines[1]. Several engine sizes are commercially available now, and additional sizes meeting the optional NO_x standards of 50%, 75%, and 90% reductions are expected to be commercially available within several years. Therefore, advanced CNG engines are a technology that can be deployed in the near-term to mitigate emissions and AQ impacts of MDV and HDV. Furthermore, the co-utilization of renewable natural gas (RNG) and renewable synthetic natural gas (RSNG) from biomass and biogas pathways can achieve deep reductions in emissions of GHG relative to both petroleum fuel vehicles and those operating on CNG from conventional fossil resources.

Shifts to advanced CNG engines from baseline (primarily diesel and gasoline) technologies will impact pollutant emissions including NO_x, particulate matter (PM), and reactive organic gasses (ROG). Shifts will occur quantitatively (in total), spatially (where), temporally (when), and in chemical composition (what); all of which subsequently influence ambient concentrations of primary and secondary air pollutant species. Further, the formation and fate of secondary air pollutants is governed by complex, non-linear atmospheric processes. For example, relative to petroleum fuel MDV and HDV, shifts to advanced CNG vehicles will incur AQ benefits, including reductions in ozone and $PM_{2.5}$, due to significant reductions in NO_x. These pollutants are associated with significant deleterious health outcomes and many regions of California experience ambient levels in excess of California and Federal health-based standards. However, without atmospheric modeling the quantification of ozone concentration reductions is not possible. Furthermore, the spatial locations and temporal periods of ground-level ozone concentration changes cannot be determined. Finally, how these impacts might be different in

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[1] https://www.arb.ca.gov/msprog/onroad/optionnox/optionnox.htm

the future given the substantial changes in emissions and emission sources is unclear. Thus, an in-depth understanding must be obtained regarding emissions from all relevant stages of technology and fuel pathways, followed by simulations of atmospheric chemistry and transport to properly evaluate potential AQ and GHG impacts of advanced CNG engines.

Therefore, the regional AQ impacts of the large-scale deployment of advanced CNG engines are currently unclear and require quantification of impacts on both primary and secondary pollutant species including ground level ozone and fine particulate matter ($PM_{2.5}$). Additionally, more information is required regarding the potential contribution of California biomass and biogas resources to RNG and RSNG production pathways to provide GHG reductions in HDV and MDV. The goal of this research is to assess the GHG emissions and AQ impacts of transitions to advanced low-NO_x CNG engines in MDV and HDV applications in California with a particular emphasis on RNG as a fueling pathway.

Air Quality Impacts

To evaluate regional AQ impacts in 2035, pollutant emissions from all end-use sectors are projected from current levels and spatially and temporally resolved. The Vision Model developed by the ARB is utilized to construct and evaluate scenarios of advanced CNG technology deployment in 2035. Scenarios are constructed beginning with both a conservative (Base Case) and more optimistic (SIP) case regarding advanced vehicle technology and fuels integration to provide spanning of potential impacts. Vehicle emissions in 2035 for each scenario are obtained from Vision and integrated into emission projections for all other sources via an emissions processing model. For example,

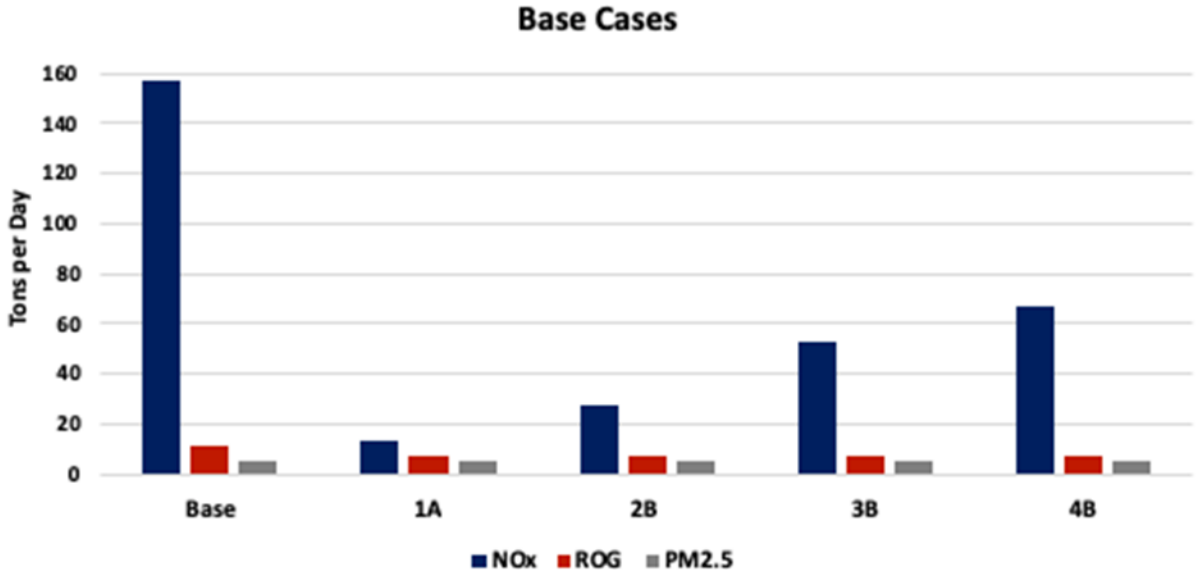
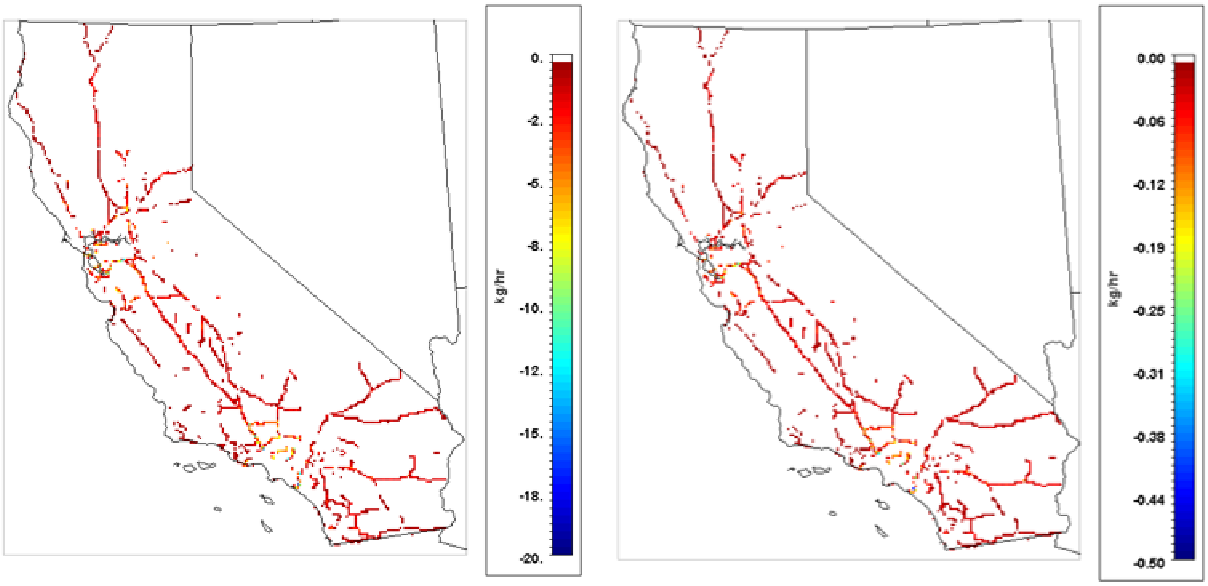


Figure 1 presents total NO$_x$ in tons per day (tpd) for the Base and Alternative Cases, while Figure 2 presents spatially resolved differences in NO$_x$ between the Base and 1B Cases. Resulting spatially and temporally resolved emission fields representative of both the baseline (Base or SIP Cases) and alternative advanced CNG cases serve as input into the Community Multi-scale Air Quality (CMAQ) model. CMAQ conducts simulations of atmospheric chemistry and transport to quantify and spatially and temporally characterize predicted changes in atmospheric pollutant species including ozone and PM$_{2.5}$. To capture the impact of seasonal dynamics on pollutant formation and fate, two modeling periods are conducted including a winter and summer episode. Results are obtained from the final day of a two week simulation and reported as differences in maximum 8 hour average (8-hr) ozone and 24 hour average (24-hr) PM$_{2.5}$. It should be noted that for AQ simulations only direct vehicle emissions are considered – impacts associated with upstream fuel pathways are not altered. Contrastingly, GHG calculations include carbon intensity factors accounting for well-to-wheel impacts.



(a) **(b)**

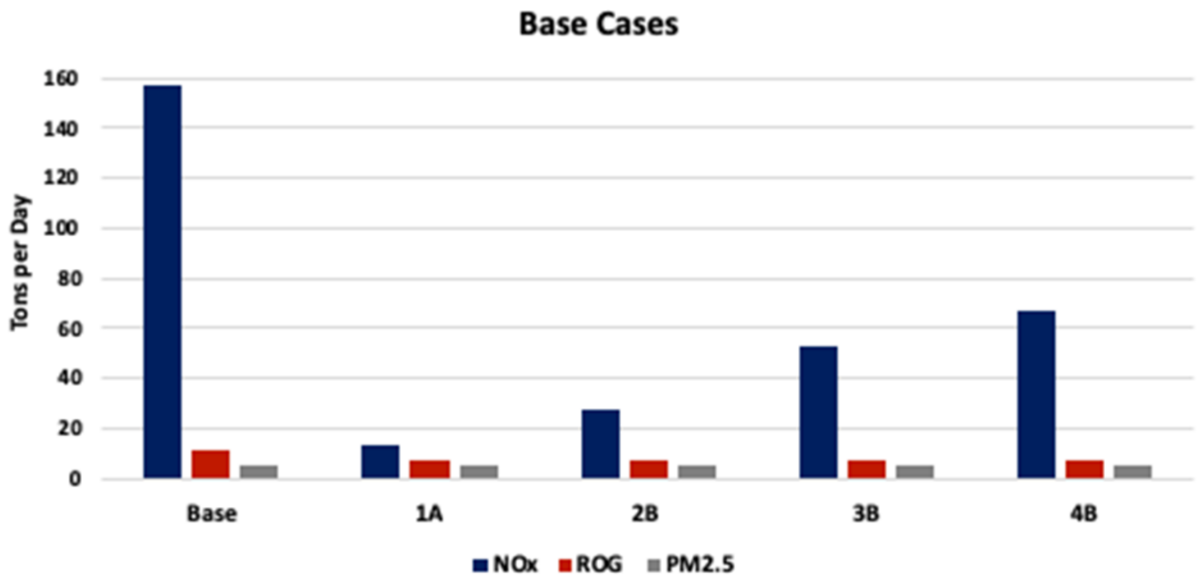
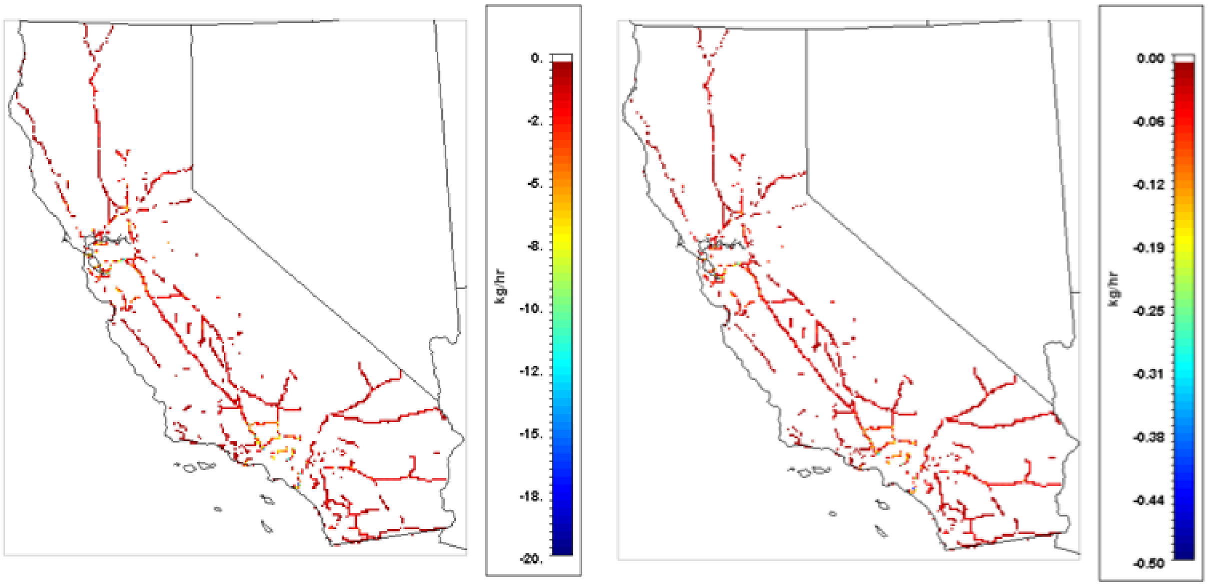


Figure 1. Total HDV and MDV emissions of NO_x, ROG, and $PM_{2.5}$ in 2035 for the Base Case and Alternative Scenarios



(a)

(b)

Figure 2. Δ Maximum 24-hour average emissions attained in the Summer 1B Case from the Base Case for (a) NO_x and (b) $PM_{2.5}$

Moving forward, the use of advanced technologies including advanced CNG engines in MDV and HDV that reduce emissions from current diesel and gasoline vehicles can significantly improve AQ in California. The use of advanced CNG engines provide reductions in NO_x emissions that reduce ground-level concentrations of ozone and $PM_{2.5}$. Reductions in ground-level ozone in summer range from -0.97 ppb to -2.77 ppb in a future where HDV and MDV technology does not significantly advance (Base Case) and from 1.16 to 1.25 ppb in a future with an assumed increases in advanced, lower emitting technologies and fuels (SIP Case). Similarly, reductions in summer $PM_{2.5}$ are predicted between -0.52 ug/m^3 to -0.60 ug/m^3 for the Base Case and -0.50 ug/m^3 to -0.51 ug/m^3 for the SIP Case. Impacts on $PM_{2.5}$ are particularly large in winter, with predicted reductions ranging from -2.71 ug/m^3 to -3.41 ug/m^3 for the Base Case and -1.41 ug/m^3 to -1.50 ug/m^3 for the SIP Case. Thus, increasing the deployment of advanced CNG vehicles achieves benefits from a future characterized by moderate advancement in MDV and HDV technologies; and from the supposition of more aggressive deployment of advanced technology portfolios in California to meet regulatory standards. The following tables report the peak predicted reductions in ozone and $PM_{2.5}$ from the Base Case for alternative cases in summer (Table 1) and winter (Table 2).

Table 1. Δ Peak ozone and $PM_{2.5}$ concentrations predicted for Summer from the Base Case

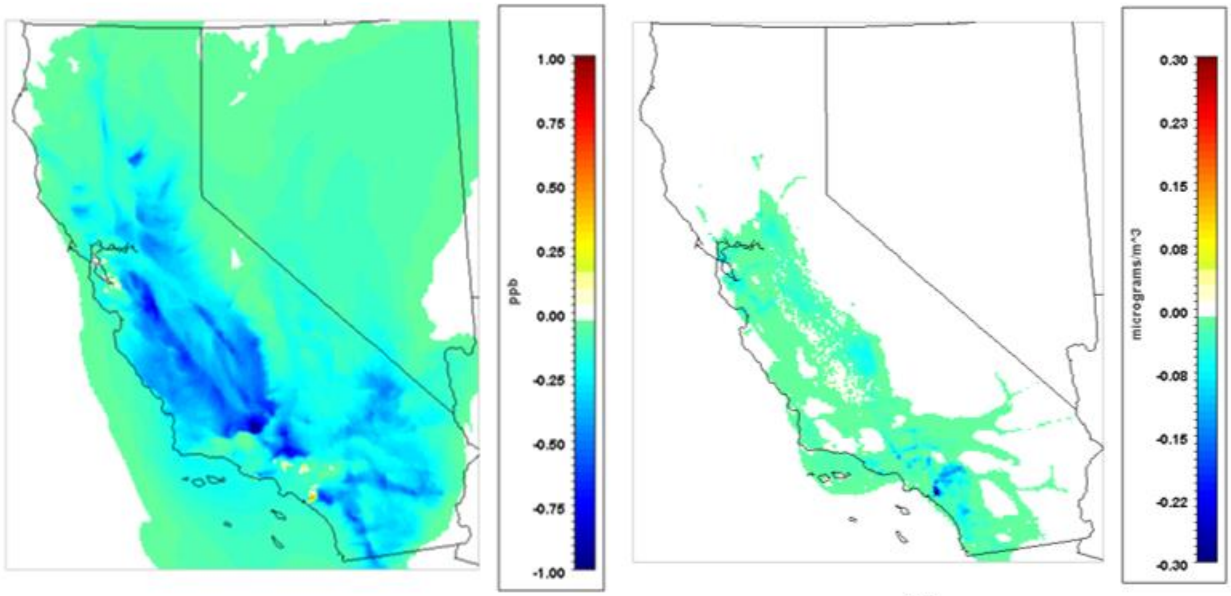
	Ground-level Ozone		Ground-level $PM_{2.5}$	
Case	**Max 1-hr**	**Max 8-hr**	**Max 1-hr**	**Max 24-hr**
1B	-5.09 ppb	-2.77 ppb	-1.28 ug/m^3	-0.60 ug/m^3
2B	-5.04 ppb	-2.73 ppb	-1.24 ug/m^3	-0.59 ug/m^3
3B	-3.91 ppb	-2.14 ppb	-1.20 ug/m^3	-0.54 ug/m^3
4B	-3.33 ppb	-0.97 ppb	-1.17 ug/m^3	-0.52 ug/m^3

Table 2. Δ Peak $PM_{2.5}$ concentrations predicted for Winter from the Base Case

	Ground-level $PM_{2.5}$	
Case	**Max 1-hr**	**Max 24-hr**
1B	-6.26 ug/m^3	-3.41 ug/m^3
2B	-6.26 ug/m^3	-3.36 ug/m^3
3B	-5.97 ug/m^3	-2.71 ug/m^3
4B	-5.91 ug/m^3	-2.71 ug/m^3

While quantification of peak reduction values is an important step, AQ assessment should also consider additional factors which, in total, determine the importance of achieved reductions, e.g., total area of impact, presence of large population centers, consideration of baseline levels,

etc.



(a) (b)

Figure 3 shows predicted difference in summer ozone and $PM_{2.5}$ for the 2A Case relative to the SIP Case, while

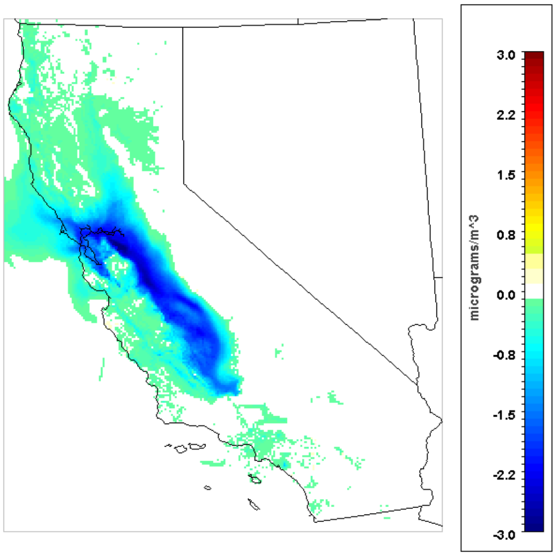


Figure 4 shows impacts on $PM_{2.5}$ in winter between the Base Case and Case 1B. Impacts are most notable in regions that currently experience unhealthy levels of air pollution including the SoCAB, Central Valley, S.F. Bay Area, and Greater Sacramento area. Many areas within these regions support very high population centers and experience some of the highest ambient concentrations of ozone and $PM_{2.5}$ in the United States[2]. Improvements in pollutant concentrations are widespread throughout the State, and thus have important implications for

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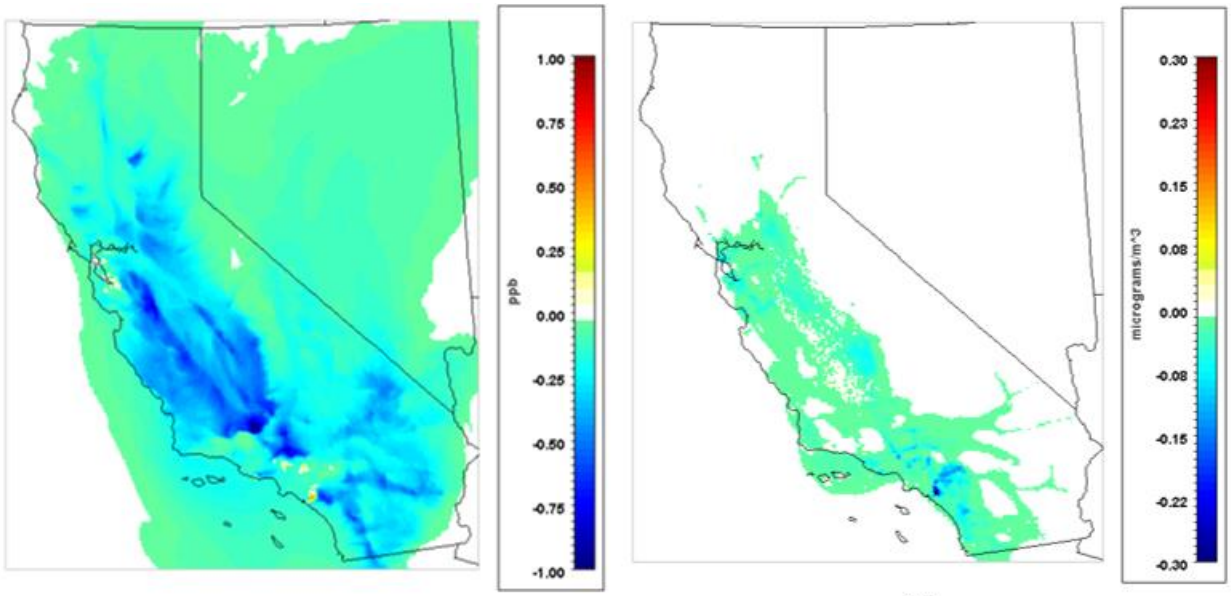
[2] http://www.lung.org/our-initiatives/healthy-air/sota/city-rankings/most-polluted-cities.html

human health benefits. Therefore, the increasing the deployment of advanced CNG vehicles above levels that are currently expected or targeted can offer important AQ benefits by reducing atmospheric pollutant concentrations in currently affected areas of the State.



(a) (b)

Figure 3. Predicted difference between the SIP and 2A Case in summer for (a) max 8-hr ozone and (b) 24-hr $PM_{2.5}$.

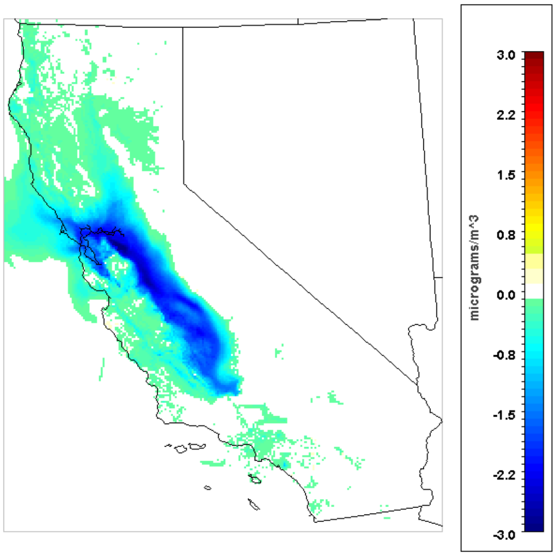


Figure 4. Predicted difference in winter episode 24-hr average $PM_{2.5}$ for Case 1B relative to the Base Case

Greenhouse Gas Emissions

In order to estimate the potential GHG impacts of transitions to advanced CNG engines in HDV and MDV scenarios are evaluated under various assumptions regarding fuel pathways to meet

CNG demand from a life cycle perspective. Total demand for CNG within a scenario is taken from the Vision Model output. Scenarios are compared to the baseline cases assuming (1) all CNG is provided from conventional fossil natural gas and (2) under a range of possible resource availabilities associated with RNG and RSNG from in-state resources. First, resource estimates are selected from the literature for pathways including RNG from landfills (LFG), wastewater treatment plants (ADG from WWTP), dairies, and municipal solid waste (MSW) and RSNG from the gasification of solid biomass (Shown in Table 3).

Table 3. Daily availability of RNG and RSNG estimated to be available for HDV and MDV fuel

	Reference 1 [3]	**Reference 2 [4]**	**Reference 3 [5]**
Fuel	[MJ/day]	[MJ/day]	[MJ/day]
WWTP RNG	27,140,931	5,274,147	--
LFG RNG	78,350,936	97,571,729	--
MSW AD RNG	--	21,096,590	--
Dairy AD RNG	--	26,370,737	--
Biomass RSNG	--	--	712,990,759

Two different References are utilized for estimates of RNG to provide a span for potential GHG impacts. In terms of in-state fuel potential, the use of solid biomass to produce RSNG represents the largest resource by a significant margin relative to the other sources. The next highest potential is estimated for landfill RNG, followed by dairy and MSW. It should be noted that the assumption that all available feedstock is available to provide fuel for HDV and MDV is highly optimistic due to competing demands from other end-use sectors and technical and economic factors associated with all pathways. Further, no assumption is made regarding several important aspects of the WTT life cycle, including the refinement and transportation of fuel to fueling stations. Therefore, these results provide an approximation of the potential GHG impacts associated with using RNG and RSNG for HDV and MDV fuel.

Next, utilizing carbon intensities for a given fuel pathway and the total demand for CNG quantified in each scenario well-to-wheels GHG emissions are calculated assuming all RNG and

RSNG is available for HDV and MDV fuels.

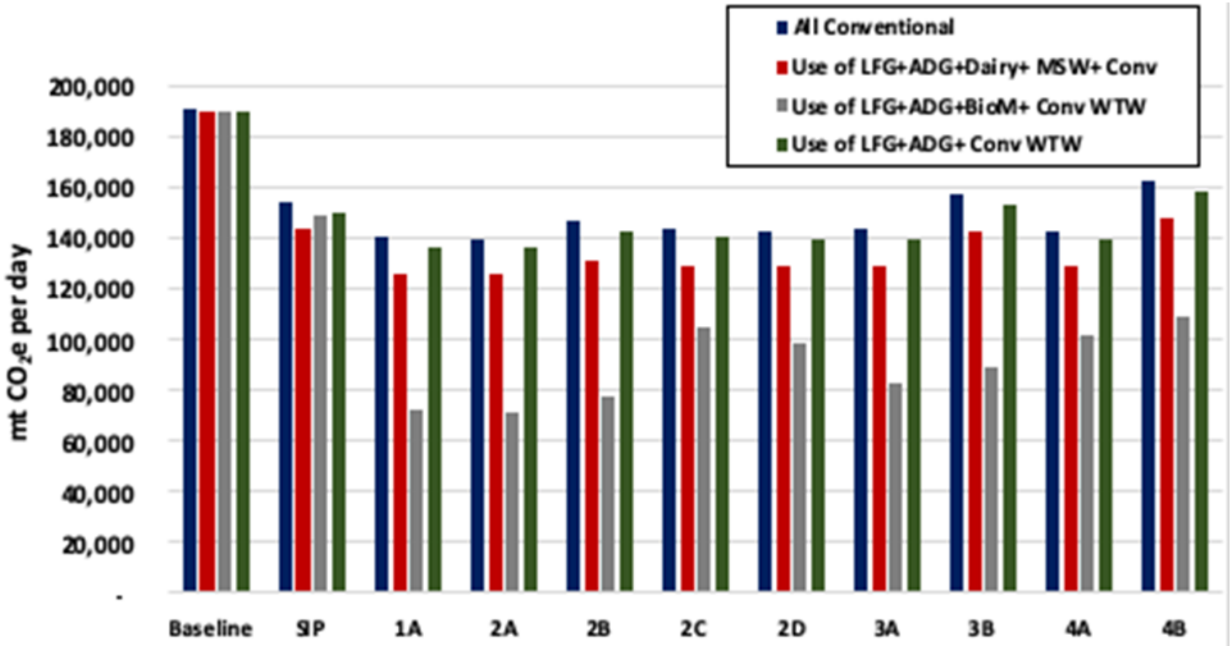


Figure 5 displays the well-to-wheels GHG emissions estimated for the considered cases assuming all conventional natural gas (All Conventional), use of LFG and ADG from WWTP (LFG+ADG+Conv), use of LFG and ADG from WWTP, Dairies, and MSW (LFG+ADG+Dairy+MSW+Conv) and use of LFG, ADG from WWTP and RSNG from biomass (LFG+ADG+BioM+Conv). The cleaner technologies and fuels assumed for the SIP Case result in an 18 to 21% reduction in GHG from the Base Case depending on the source of CNG. Reductions for advanced CNG scenarios are estimated even when all CNG is derived from fossil due to assumed increases in vehicle efficiency and a modest reduction in carbon intensity for natural gas relative to conventional diesel and gasoline fuels. Relative to the Base Case, reductions in GHG range from 14 to 26% assuming all CNG is of fossil origin, 17 to 28% assuming LFG and AD from WWTP is available, 22 to 34% assuming RNG from LFG and ADG from WWTP, dairies, and MSW, and 42% to 62% assuming RNG from LFG and ADG from WWTP and RSNG are available to meet demand. Relative to the SIP Case, reductions in alternative SIP Cases range from 6 to 9% assuming all CNG is of fossil origin, 9 to 11% assuming LFG and AD from WWTP is available, 16 to 18% assuming RNG from LFG and ADG from WWTP, dairies, and MSW, and 34 to 53% assuming LFG, AD from WWTP and RSNG is available to meet CNG demand. The impacts of in-state resource availability are evident in that the largest reductions in GHG occur under the assumption that the gasification of solid biomass provides a significant amount of RSNG to meet fueling demands.

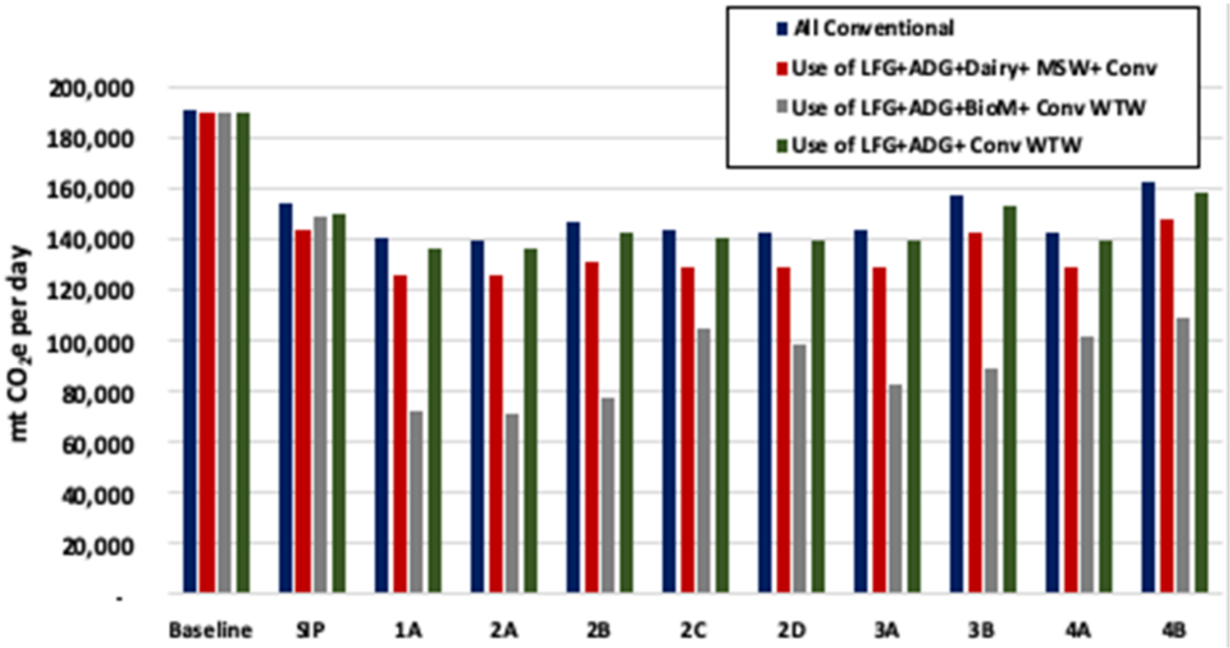


Figure 5. Well-to-wheels GHG emissions estimated for considered cases under different CNG fuel pathway assumptions

Conclusions

The following are key conclusions from this work:

- Expanding the deployment of advanced CNG MDV and HDV can reduce summer ground-level ozone concentrations in key regions of California including the SoCAB, Central Valley, S.F. Bay Area, and Sacramento. Reductions could exceed -1.25 to -3.77 ppb depending on the evolution of advanced vehicle technologies within HDV and MDV fleets.
- Advanced CNG MDV and HDV can also achieve reductions in ground-level $PM_{2.5}$ in key regions of California including the Central Valley and SoCAB. Impacts in winter are particularly notable with some areas experiencing reductions exceeding -1.50 to -3.41 ug/m^3 in the Central Valley. Highlighting the seasonal nature of PM impacts, predicted reductions for summer peak in the SoCAB at -0.51 to -0.60 ug/m^3.
- The use of advanced CNG engines for in-state HDV (approximately 60% of total HDV) could improve summer ozone by 1.18 ppb and $PM_{2.5}$ by -0.50 ug/m^3 in summer and 1.43 ug/m^3. This is notable due to challenges associated with forcing technology shifts for out-of-state or international HVD and MDV.
- The largest AQ benefits are associated with reducing emissions from HDV. The results highlight the importance of continuing the development and advancing the deployment of advanced CNG engines in larger vehicle classes.

- While the mass of emitted $PM_{2.5}$ is assumed to be similar for advanced CNG engines relative to advanced diesel and gasoline engines, the chemical composition of emitted PM may differ substantially with implications for human health impacts. This is an issue that would benefit from further study, including toxicological research.
- In-state RNG pathways can meet the CNG demand estimated for both baseline cases, including the less optimistic case of advanced technology deployment (Base) and more optimistic case including additional alternative technologies and fuels (SIP). The SIP Case is representative of the most plausible outcome for the sector in 2035 and it is likely demand could be met entirely with in-state RNG in 2035 if levels of advanced CNG increase moderately within HDV and MDV fleets.
- For the high total CNG demand estimated for the majority of Base alternative cases, in-state resources are unable to entirely meet CNG demand and some portion (5 to 35%) must be met with fossil CNG. Conversely, demand in the majority of the cleaner technology mix cases can be met with renewable CNG from in-state resources. **However, this requires the availability of significant amounts of CNG from solid biomass resources, and that use by HDV and MDV be prioritized over other end-uses.** When considering only RNG pathways from LFG and ADG from WWTP, dairies, and MSW (i.e., no biomass gasification) in-state resource can provide 22 to 30% of total CNG. The results highlight the importance of advancing solid biomass pathways for renewable transportation fuel and the relatively lesser availability of in-state RNG.
- Advanced CNG HDV and MDV can moderately reduce GHG emissions if fossil natural gas is used (14 to 26%), particularly if the baseline fleet is composed of less efficient diesel and gasoline technologies. For the more realistic assumption of a cleaner mix of technologies and fuels, the reduction is less (6 to 9%) if only fossil natural gas meets CNG demand.
- The use of RNG can provide GHG reductions in alternative cases of 16 to 34% for the Base Cases and 9 to 18% for the SIP Cases depending on the assumed resource mix. If the gasification of solid biomass is included to provide RSNG reductions could reach 42 to 62% for the Base Case to 34 to 53% for the SIP Cases

Introduction

As a fundamental part of California's on-road goods movement sector, medium- (MDV) and heavy-duty (HDV) trucks provide important services to California's economy. However, emissions from MDV and HDV current represent a significant source of pollution within the State impacting regional air quality (AQ) with ensuing harmful health impacts to California citizens. Additionally, MDV and HDV emissions of climate forcing greenhouse gasses (GHG) must be reduced to achieve State climate goals established under AB 32 [1]. Therefore, transitions from current vehicles operating on petroleum fuels to cleaner, lower emitting technologies and fuels must be undertaken in California to ensure environmental quality goals are met.

Executive Order B-32-15 required the state of California to establish the Sustainable Freight Action Plan (SFAP) to outline the transition to a more efficient, more economically competitive, and less polluting freight transport system [6]. Specifically, environmental targets for the SFAP include reducing exposure to air toxics and assisting the State in meeting health-based air quality standards and climate change goals. Guidelines for transitions to cleaner technologies within the SFAP include maximizing near-zero emission freight vehicles and equipment operating on renewable energy by 2030.

In order to reach established environmental and energy goals, California must achieve significant reductions in emissions from mobile on-road sources including MDV and HDV. Recent technological advancements have made available stoichiometric spark ignition CNG engines that can significantly reduce emissions from HDV and MDV by utilizing a systems approach combining advanced three-way catalysts with engine management strategies. Cummins Westport's 8.9 liter (L) SI CNG engine has been certified by the U.S. EPA and the ARB to a 0.02 gram per brake horsepower-hour (g/bhp-hr) optional NO_X standard and is commercially available [2]. It is expected that other engine sizes (6.7L, 9L, 12L) meeting one of the optional NO_x standards (0.02, 0.05, 0.1 g/bhp-hr) will become available within the next 5 years. Advanced CNG vehicles, once commercialized, can deliver important near-term opportunities to significantly reduce NO_x emissions, and with the use of renewable natural gas, could additionally provide notable GHG emission reductions.

The 8.9 L engine is applicable for MDV including trucks, urban transit and school buses, and refuse hauler applications. Cummins Westport has announced a 6.7L, 9L, and 12L for model year 2018[3]. These engines will be applicable for a range of HDV and MDV applications including regional haul trucks and tractors, vocational and transit, school bus, and refuse applications. The 6.7 to 12 L engines are designed for truck and bus applications up to 80,000 pounds and

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[3] http://www.cumminswestport.com/press-releases/2017/cummins-westport-moves-to-zero-with-new-natural-gas-engines

can be customized to meet individual vocational requirements [2]. The vehicles are expected to have sufficient range to offer route flexibility without requiring in-route refueling, e.g., on highway natural gas trucks can have over 700 mile range[4]. Therefore, it is assumed for this study that advanced CNG engines will be available and suitable for all MDV and HDV applications in the horizon year for this work (2035).

The two pollutants utilized to assess AQ for this work are $PM_{2.5}$ and ground-level ozone. Both represent a historical air pollution concern in California and are associated with prominent detrimental human health impacts supported by a large body of scientific literature [7-9]. Ozone is not a directly emitted species and forms in the atmosphere during reactions associated between NO_x and ROG in the presence of sunlight [10]. Ozone is an important component of photochemical smog, representing the regulated pollutant in California's efforts to reduce the impacts. $PM_{2.5}$ is both directly emitted and forms in the atmosphere during reactions associated with gaseous precursor emissions with both pathways contributing to total atmospheric levels. Therefore, atmospheric concentrations of ozone and $PM_{2.5}$ serve as appropriate metrics in the evaluation of AQ impacts associated with technological shifts targeting AQ improvements.

PM is composed of wide range of finely divided solid or liquid components that include ash, soot, smoke, aerosols, fumes, mists, and other condensing vapors which suspend in the atmosphere. $PM_{2.5}$ refers to that portion that are 2.5 microns or less in width and are particularly concerning for human health due to their ability to travel deeply into the respiratory tract. $PM_{2.5}$ both directly emitted from anthropogenic activities and formed in the atmosphere during processes such as the reaction of gaseous pre-cursor emissions and including NO_x, ROG, ammonia, and SO_x. These chemical pathways often occur distant from emission sites and are significantly impacted by seasonal events such as temperature and relative humidity. Emissions of primary PM and secondary PM precursors from industrial and urban sources, such as those found in several areas of California, lead to elevated levels of atmospheric $PM_{2.5}$ [11]. Thus, two pathways exist whereby emission reductions from advanced technologies and fuels can decrease atmospheric concentrations of $PM_{2.5}$. First, reductions in emitted $PM_{2.5}$ from vehicle tail-pipes reduce atmospheric burdens directly. Second, reductions in pre-cursor emissions of NO_x and ROG provide reductions in secondary (i.e., formed) $PM_{2.5}$. It should be noted that the complicated reactions associated with the second pathway may result in impacts that differ spatially and temporally from those in the first pathway. However, as there is no discernable way to identify which portion of predicted $PM_{2.5}$ is primary vs. secondary, both are shown as a net impact in the following figures.

Ambient (i.e., baseline) pollutant concentrations are a key aspect in interpreting AQ impacts as locations with poor AQ as a baseline will benefit the most from improvements (or vice versa). In

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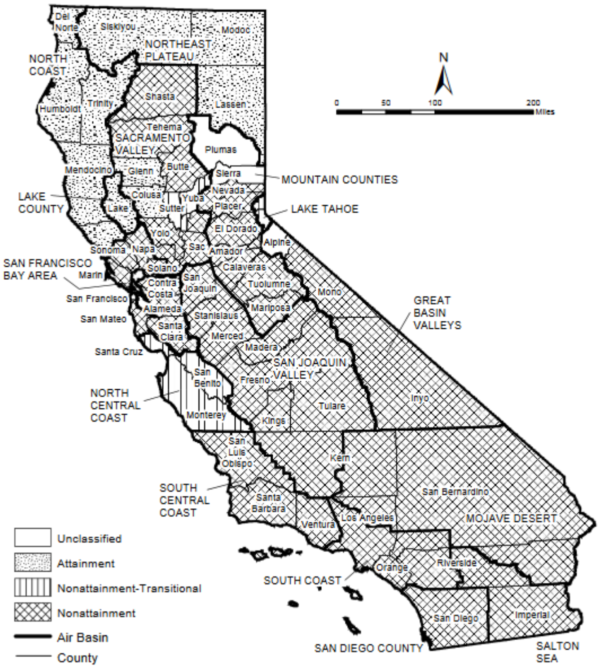
[4] http://ngvgamechanger.com/pdfs/GameChanger_FullReport.pdf

other words, locations with poor AQ are where the improvements are needed most. Many California regions experience poor AQ which heighten the importance of any attained improvements have elevated ground-level ozone and $PM_{2.5}$ that regularly exceed Federal health-based standards and contain large urban populations [12] and improvements are being pursued in California to mitigate deleterious human health events related to pollution exposure [13]. These regions include SoCAB which includes Orange County and the non-desert areas of Los Angeles, San Bernardino, and Riverside Counties. SoCAB is associated with some of the worst air pollution in the U.S., represented by non-attainment for multiple pollutants including ozone (i.e., see Figure 6) and $PM_{2.5}$[5]. Also shown in Figure 6, the S.F. Bay Area, Central (i.e., San Joaquin) Valley, and Greater Sacramento Valley regions experience poor AQ and improvements are particularly needed.



Source Date:
December 2015
Air Quality Planning Branch, AQPSD

Figure 6. California NAAQs designations for ground-level ozone. From: https://www.arb.ca.gov/desig/adm/adm.htm

Thus, reductions in NO_x from advanced CNG engine deployment can attain important benefits to AQ in California regions, with a particular emphasis on two key pollutant formation mechanisms. First, emission decreases will reduce ground-level concentrations of ozone – a key ingredient in photochemical smog formed from reactions between emissions of NO_x and reactive organic gasses (ROG) in the presence of sunlight. Second, reductions in NO_x will reduce

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[5] http://www.aqmd.gov/docs/default-source/clean-air-plans/air-quality-management-plans/2016-air-quality-management-plan/final-2016-aqmp/final2016aqmp.pdf?sfvrsn=15

levels of fine particulate matter ($PM_{2.5}$) via secondary formation mechanisms associated with nitrate. Ozone and $PM_{2.5}$ are pollutants of high concern for California as both are associated with significant human health impacts, and many regions of the State are in non-compliance with Federal health-based standards.

However, attaining a thorough understanding of the AQ impacts of advanced CNG replacement of conventional petroleum fuel HDV and MDV is complex and requires more than just quantifying emission reductions. Ambient pollutant concentrations are influenced by a highly diverse range of numerous factors. The complexity associated with the formation and fate of atmospheric pollution complicates an understanding of how advanced CNG vehicles will impact AQ in California regions in the future. Specifically, the atmospheric chemistry and physical processes associated with the formation and fate of ground-level ozone from pre-cursor emissions (i.e., NO_x and ROG) significantly reduces the value of only quantifying emission reductions when studying AQ impacts [14]. Similarly, ground-level concentrations and compositions of PM in California are governed by multifaceted conditions including sources of emissions, amounts of directly emitted PM, and the atmospheric processes associated with secondary PM formation that yield spatial and temporal variation in source-related impacts and potential mitigation measures [15]. Therefore, detailed atmospheric models must be used to conduct simulations of chemistry and transport to account for the spatial and temporal distribution of pollutant concentrations in order to assess how alternative fueled vehicles may impact ground-level ozone and $PM_{2.5}$ in California.

Methods

To accomplish the research objectives the following steps are required:

- Develop a set of future scenarios for deployment of advanced low-NO_x CNG engines in various vehicle classes comprising the MDV and HDV sectors in California.
- Leverage prior research of biogas and biomass resources in California to consider potential in-state resource pathways to support RNG and RSNG vehicle fueling.
- Quantify changes in lifecycle GHG emissions from baseline for scenarios and compare and contrast to identify strategies that maximize reductions from California’s resources.
- Via an emissions processing model (SMOKE) apply quantified emission changes and produce spatially and temporally resolved emission fields.
- Conduct simulations of atmospheric chemistry and transport via a photochemical AQ model (CMAQ) to quantify and spatially resolve impacts on primary and secondary pollutants including ozone and $PM_{2.5}$.

Scenario Development

The following sections describes the methods used to develop scenarios of the MDV and HDV sector in California in 2035 designed to span a range of possible outcomes for the deployment of advanced CNG engines. The scenarios seek to provide insight into GHG and AQ impacts associated with various fleet penetration levels in different vehicle classes, i.e., MDV vs. HDV. Additionally, the impact of in-state trucks relative to out-of-state trucks is considered to compare the AQ and GHG benefits.

Vision Model

The Vision Scenario Planning Model version 2.1 is utilized to produce scenarios of advanced CNG deployment in California in 2035. Vision was developed by the California Air Resources Board and allows users to conduct multi-pollutant assessments for the transportation sector system-wide in California [16]. A schematic of the model framework is provided in Figure 7. Vision accounts for vehicle sales, activity, technologies, fuels, and efficiencies to estimate energy demand and emissions (both vehicle and upstream) for various transportation outcomes. The Vision model incorporates the retirement of a fraction of vehicles, the purchase rate at which vehicles are introduced for various categories, and the emissions factors related to each category and other inputs in order to create an emission inventory for a specific calendar year. These features allow for scenario development to study the introduction of novel technologies and fuels, current and future regulations, etc., in terms of energy and emissions. The Vision Model 2.1 is comprised of 6 different modules, with 5 pertaining to specific transportation sectors and a module dedicated to energy. For this study, the Heavy Duty Vehicle Module including trucks with over 8,500 pounds gross vehicle weight rating is used to develop a database of the emissions for difference scenarios introducing advanced CNG engines into the MDV and HDV population for the year 2035. The HDV module is a scenario tool that uses EMFAC2014 data as a baseline with the option for users to modify range of parameters that effect emissions including MDV and HDV population, VMT, efficiency, and emission factors. Scenarios incorporating advanced technology introduction can then be modeled to evaluate impacts on emissions, fuel, and energy demand. Advanced technologies incorporated in the HDV module for trucks include gasoline, diesel, battery electric, natural gas, and hydrogen fuel cell powered vehicles.

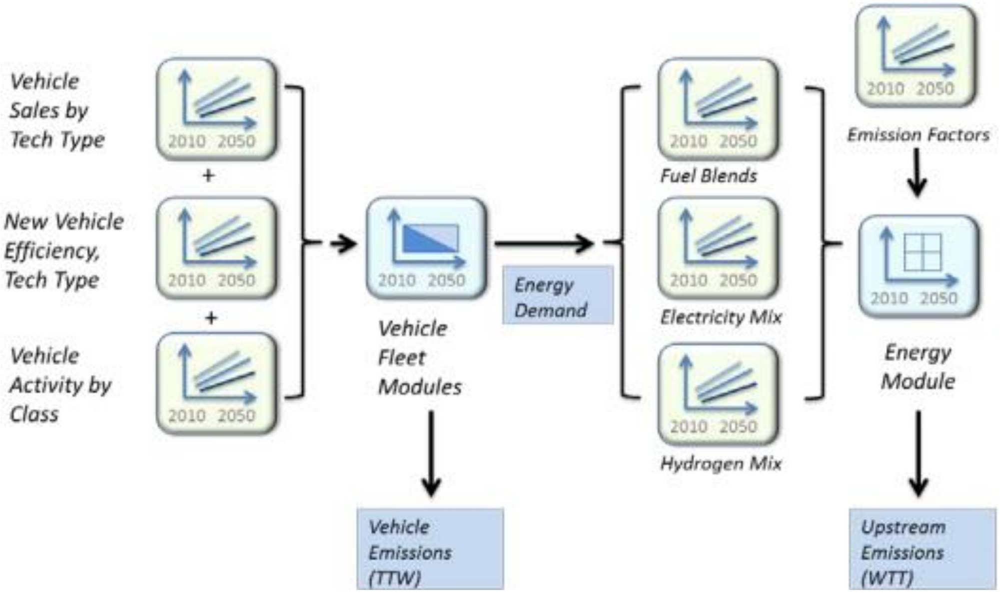


Figure 7. Framework for the Vision 2.1 Model. From [16].

Description of Base Case and SIP Scenarios

The HDV module within the Vision model generates two sets of emission databases by design and both are used in this work as baseline outcomes to compare with alternative scenarios of advanced CNG trucks. One database is the baseline which considers that for the current year and the future year the only emission control regulations are those the current regulations set in place, i.e., the **Base Case**. The regulations considered in the baseline are the following:

- **GHG Phase I:** US EPA's measure to improve fuel efficiency and reduce green-house gas emissions from model years 2014-2018 heavy duty trucks
- **ARB Tractor-Trailer Regulation:** requires the use of aerodynamic tractors and trailers to reduce GHG emissions
- **ARB Truck and Bus Rule:** ARB's measure to accelerate turnover of heavy duty trucks to the on-road 2010 emission standard by 2023
- **ARB Drayage Truck Regulation:** Requires drayage trucks in South Coast to upgrade to 2007 or newer engines, with 2010 or newer required in 2023
- **ARB Public Fleets Rule and Solid Waste Collection Vehicle Rule :** Fleets must apply the Best Available Control Technology (BACT) to reduce PM emissions, with multiple options depending on the truck model year

The second dataset generated by the HDV module from Vision considers the State Implementation Plan (SIP) measures. The **SIP Case** includes the controls and regulations described in California's SIP document which affect the HDV population. These measures include:

- **GHG Phase 2 Regulation:** Reductions in CO_2 and fuel consumptions phase in from 2018 to 2027 with 5 to 25 percent efficiency improvements depending on vocation beyond currently adopted GHG Phase I and ARB's Tractor-Trailer Regulation
- **Federal Low-NO_x Engine Standards:** Combining the Low-NO_x Engine Standards and Lower In-Use Emission Performance level measures, a flat 90 percent reduction in NO_x emissions from the current 2010 standard for all exhaust processes throughout the life of the vehicle. Assumed 100% of model year 2024 and newer trucks will be impacted by the measure. The splits between diesel and natural gas based on technology availability, vocation and infrastructure. Long-haul trucks would still be dominated by low-NO_x diesel while local delivery trucks assumed to have higher penetration of natural gas low-NOx
- **California Only Low-NO_x Engine Standards:** Similar to Federal Low-NOx Engine Standards but only impacts vehicles purchased new in California. Since significantly more used federal standard trucks will migrate to California than used trucks meeting California standard migrating out, the benefit of California only Standard would be a fraction of the reduction achieved with Federal

Standards. Simplified purchase fractions and derived survival rates to simulate the overall impact of California Only Low-NO_x Standard.

- **Zero Emission Vehicles for Last Mile Delivery Trucks:** several local Class 3 to 7 vehicle categories in EMFAC2014 that are most likely to include fleets impacted by this measure. Based on projected heavy duty ZEV population for the measure ARB assumed 2.5 percent of new sales starting 2020 to be battery or fuel cell technologies and increasing to 10 percent by 2025 which remain flat thereafter

Description of Alternative Scenarios

Using the two baseline datasets (Base and SIP) as starting points, additional scenarios are developed to assess the increased implementation of advanced CNG engines across MDV and HDV categories. The scenarios described below consider a higher usage of advanced CNG engines over the initial assumed penetration by displacement of gasoline or diesel engines. The scenarios consider a mix of technologies including various diesel and gasoline engines, and for some scenarios hydrogen fuel cell and battery electric vehicles. However, in this work it is assumed that advanced CNG vehicles are the predominant advanced technology in the MDV and HDV population.

Base Case: Considers no implementation of emission reduction programs to current vehicles using a business-as-usual approach. The Base Case represents a “frozen” technology case with changes occurring only in total demand for VMT, etc. Comparison with the Base Case allows for insight into the role that advanced CNG can play in improving AQ in coming decades from current levels.

State Implementation Plan (SIP): Assumes successful implementation of current legislation to reduce emissions including the introduction of US EPA GHG Phase 2 vehicles starting in 2018, advanced, low-NO_x emission engines for gas, diesel, and CNG trucks beginning 2024, and introduction of both electric and hydrogen zero emission last-mile delivery trucks starting in 2020. Comparison with the SIP Case allows for insight into reductions obtained from California investment in all advanced HDV and MDV technologies, and the role of advanced CNG vehicles within the portfolio of advanced technologies.

1B: With the Base Case as a starting points, vehicles in all categories, both MDV and HDV, completely transition to advanced CNG engines. Case 1B provides an upper bound for the impacts of advanced CNG engines in California.

2A: With the SIP Case as a starting point, includes a complete transition of HDV categories into advanced CNG engines. For the MDV, 50% of the vehicle population transition to advanced CNG vehicles. Advanced CNG engines replace diesel engines for those categories where the technology is able to. Additionally, an increase in efficiency is assumed for advanced CNG engines in both MDV and HDV.

2B: With the Base Case as a starting point, considers the transition of 50% of the MDV population to advanced CNG engines, while 100% of HDV population transitions to advanced CNG engines. Both categories considers an increase in the efficiency of the technology through the years. Additionally, an increase in efficiency is assumed for advanced CNG engines in both MDV and HDV.

2C: Using the SIP case as a starting point, considers the transition 50% of the MDV population to advanced CNG engines by replacing vehicles running on low-NO$_x$ diesel engines in the original SIP case. For HDV, the case considers the transition from diesel to advanced CNG engines for those vehicles categories for which the advanced CNG engine is most likely to be adopted in the 2035 time frame (Table 5). The scenario also includes the efficiency increases within the MDV and HDV.

2D: Starting with the SIP Case, 50% of MDV population transitions to advanced CNG engines by replacing the population which is running on low-NO$_x$ diesel engines from the original SIP case. For the HDV population, the case looks at the use of advanced CNG engine, rather than a low-NO$_x$ diesel engine, for those vehicles which are registered only to California (i.e., in-state trucks). An increase in efficiency is considered in both vehicle categories. The goal of this scenario is to provide insight into the impacts of alternative technologies only deployed for in-state trucks, as out-of-state trucks may be slower to transition to cleaner technologies.

3A: Starting with the SIP Case, considers all MDV vehicles are powered by advanced CNG engines rather than a mixture of technologies of including hydrogen fuel cell, battery electric, gasoline, and diesel vehicles. For HDV, low-NO$_x$ diesel engines were replaced by advanced CNG engines for the categories in which they were applicable. For both MDV and HDV an increase in efficiency is considered.

3B: Starting with the Base Case, considers all HDV population transitioning and 50% of MDV population to advanced CNG engines. The scenario also includes any efficiency improvements from current engines.

4A: Starting with the SIP Case, considers the implementation of advanced CNG engines in 50% of MDV and 50% of HDV population. Advanced CNG engines replace diesel engines of those categories in which they are most likely to be implemented in the future. The scenario also includes efficiency improvements.

4B: Starting with the Base Case, considers the implementation of advanced CNG engines for 50% of MDV and 50% of the HDV population. CNG engines replace diesel engines of those categories in which they are most likely to be implemented in the future. The scenario also includes efficiency improvements.

Table 4. Summary of Considered Scenarios

Scenario	Case Origin	HDV Assumption	MDV Assumption
Base	---	Current regulations and engines	Current regulations and engines
SIP	Base	Measures in SIP document	Measures in SIP document

Scenario	Case Origin	HDV Assumption	MDV Assumption
1B	Base	100% Advanced CNG	100% Advanced CNG
2A	SIP	100% Advanced CNG	50% Advanced CNG
2B	Base	100% Advanced CNG	50% Advanced CNG
2C	SIP	All likely vehicles Advanced CNG	50% Advanced CNG
2D	SIP	100% In-state vehicles Advanced CNG	50% Advanced CNG
3A	SIP	50% Advanced CNG	100% Advanced CNG
3B	Base	50% Advanced CNG	100% Advanced CNG
4A	SIP	50% Advanced CNG	50% Advanced CNG
4B	Base	50% Advanced CNG	50% Advanced CNG

Currently, existing advanced CNG engines are predominantly used in refuse trucks. However, there is significant interest in expanding the use of advanced CNG engines to additional MDV and HDV vocations. For scenarios assuming 50 percent of the MDV and HDV vehicle population transition to advanced CNG engines, there are some vocations which have more certainty associated with the appropriateness of the engine for the given vocation and thus the engine is more likely to be deployed within the sector. Table 5 shows the categories which are most likely to adopt advanced CNG engines in by the year 2035. These categories are chosen for deployment in the SIP 2C alternative scenario.

Table 5. MDV and HDV categories most likely to adopt advanced CNG engines by 2035

HEAVY-DUTY CATEGORIES	MEDIUM-DUTY CATEGORIES
• Heavy-Heavy Duty Diesel Drayage Trucks • Heavy-Heavy Duty Diesel Public Fleet Truck • Heavy-Heavy Duty Diesel Single Unit Truck • Heavy-Heavy Duty Diesel Refuse Truck • Heavy-Heavy Duty Diesel Public Fleet Truck • Heavy-Heavy Duty Diesel Utility Fleet Truck • Heavy-Heavy Duty Gasoline Truck	• Light-Heavy-Duty Trucks (GVWR 8,501-10,000 lbs) • Light-Heavy-Duty Trucks (GVWR 10,001-14,000 lbs) • Power Take Off • Medium-Heavy Duty Diesel Agriculture Truck • Medium-Heavy Duty Diesel Instate Construction Truck with GVWR>26,000 lbs • Medium-Heavy Duty Diesel Instate Construction Truck with GVWR<=26,000 lbs • Medium-Heavy Duty Diesel Instate Truck with GVWR>26,000 lbs • Medium-Heavy Duty Diesel Instate Truck with GVWR<=26,000 lbs • Medium-Heavy Duty Diesel Public Fleet Truck • Medium-Heavy Duty Diesel Utility Fleet Truck • Medium-Heavy Duty Gasoline Truck

Depending on the assumptions for a given Case, the vehicle population and daily VMT of HDV and MDV by technology type is projected from current to the year 2035. Figure 8 displays the evolution of the MDV and HDV fleets to 2035 for Case 1B developed in the Vision Model. As can be seen, all vehicles transition to advanced CNG engines from 2007-2009 and 2010 Standard petroleum fuel technologies by 2035. While this is a highly optimistic outlook on advanced CNG engines, Case 1B is designed to serve as an upper bound for possible impacts.

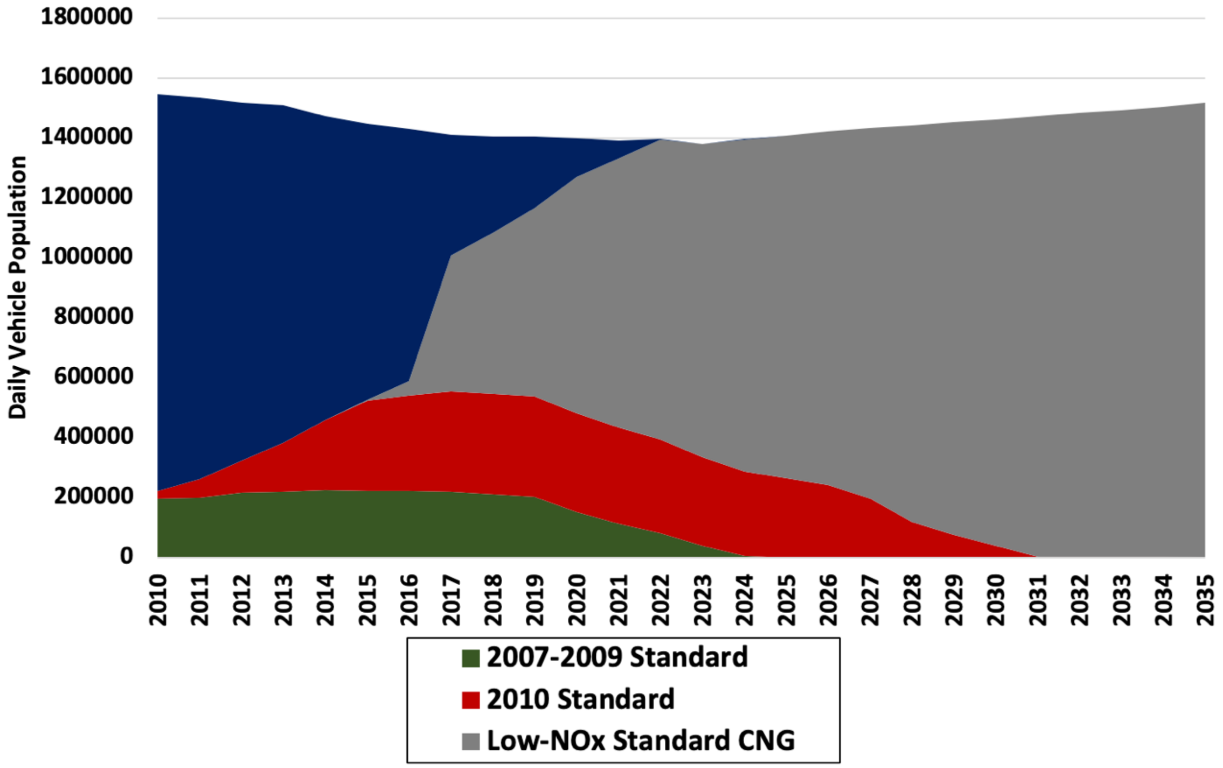


Figure 8. Daily vehicle population of MDV and HDV to 2035 in Case 1B. 2007-2009 Standard and 2010 Standard refer to petroleum fuel vehicles.

Conversely, Figure 9 displays the evolution of the MDV and HDV fleets to 2035 for Case 2D which assumes all in-state HDV transition to advanced CNG. Case 2D is constructed based on the SIP Case which assumes cleaner technologies are implemented in addition to CNG including low-NO_x standard diesel and gasoline. Additionally, battery electric and hydrogen vehicles in last mile delivery applications are included, although at a low total percentage. Case 2D provides a more realistic outcome for 2035 relative to Case 1B as the SIP Case is designed to provide emission reductions needed to meet AQ mandates and in-state vehicles will likely be more straightforward to encourage shifts to advanced CNG (relative to out-of-state and international vehicles)

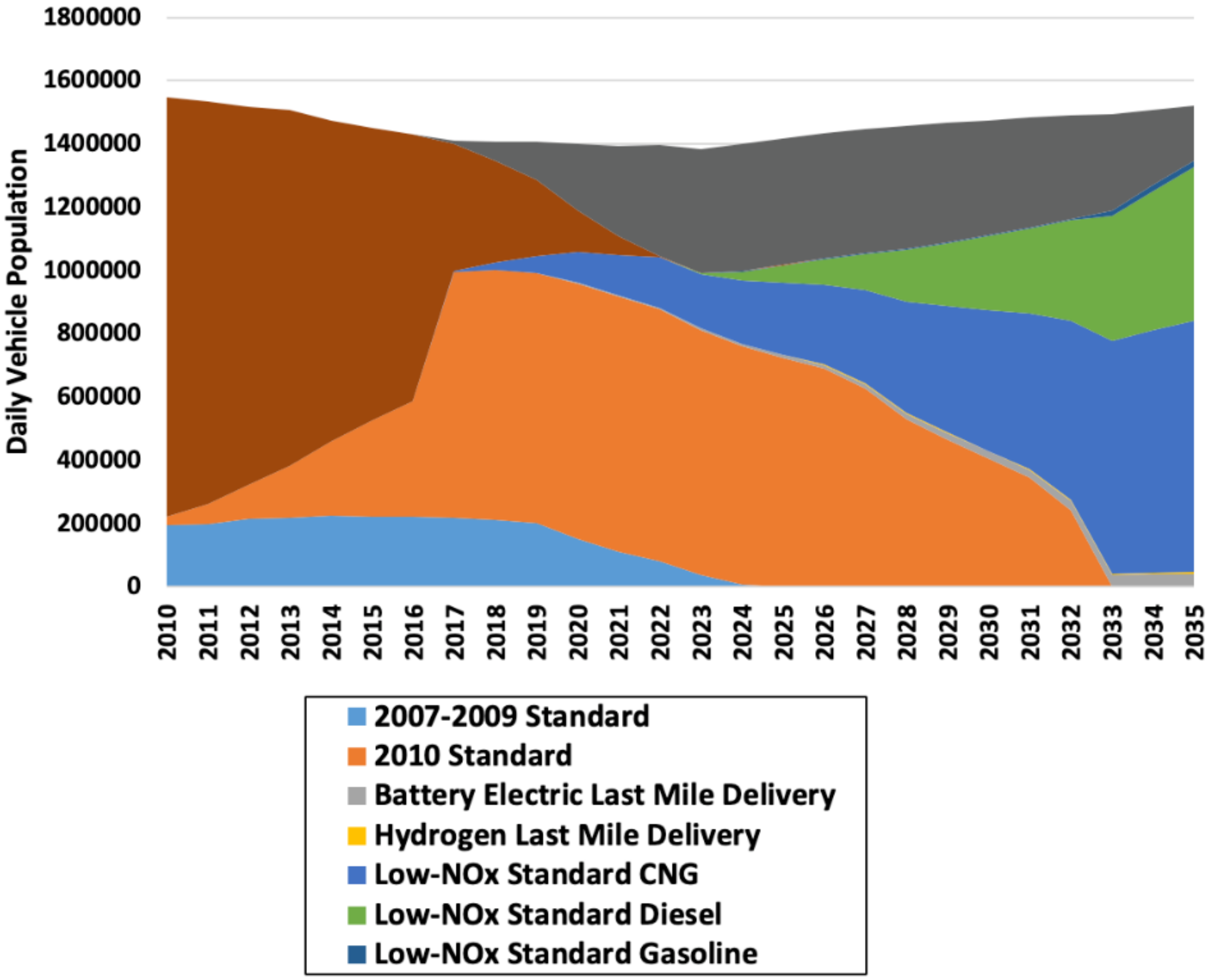


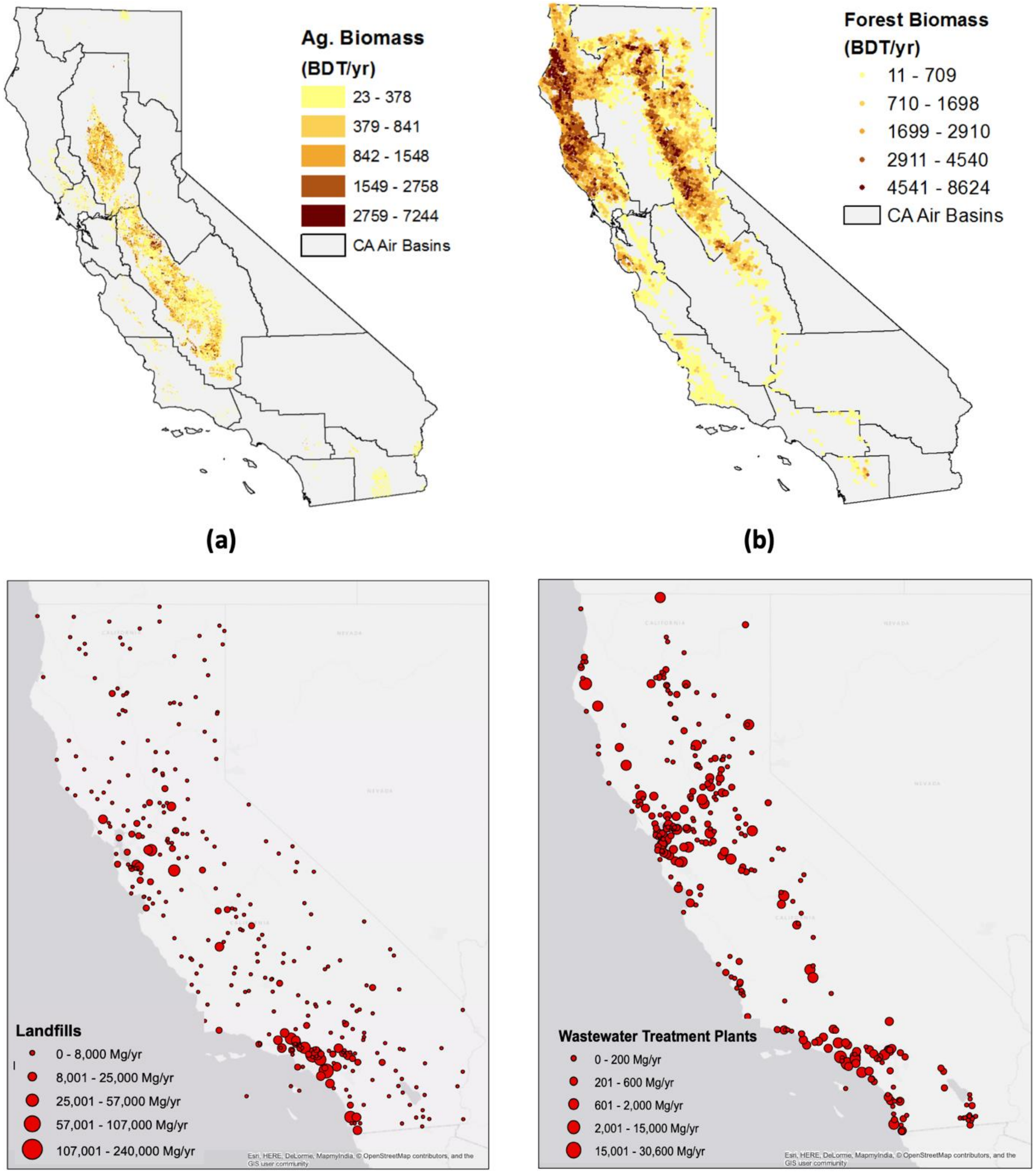
Figure 9. Daily vehicle population of MDV and HDV to 2035 in Case 2D.

While the majority of cases are designed to span the possible deployment of advanced CNG (i.e., between 50 to 100% of total vehicles), two cases were developed to assess the impact of additional considerations associated with vehicle deployment. Case 2C assumes the complete deployment within vehicle vocations expected to be the most feasible for advanced CNG technologies (listed in Table 5). The results from Case 2C provide an approximation of how the HDV fleet may evolve if advanced CNG engines are not commercially developed. The fraction of the HDV fleet that transitions to advanced CNG in Case 2C is 41%. Case 2D assumes the complete deployment of advanced CNG only for those HDV that are registered in the State, i.e., in-state vehicles. Case 2D is designed to consider the impact of challenges associated with the regulation of out-of-state and international vehicles. The fraction of the HDV fleet that transitions to advanced CNG in Case 2D is 60%.

Biogas Resource Estimate

Combining advanced CNG engines with renewable, low-carbon gaseous fuels is a necessary step to reducing GHG emissions from the HDV and MDV fleet. To inform and assess the potential for

California biomass and biogas resources to provide fuel for MDV and HDV, estimates of in-state resource availability were conducted. The results from a California Energy Commission funded study were utilized to estimate the resource availability of certain biogas feedstocks, including from landfills and wastewater treatment plants (WWTP) [3]. Figure 10 shows the location of biomass and biogas resources in California and the potential for each feedstock. Considering the production of RNG from landfills and WWTP, there is a total potential of 1,121,986 Megagrams of biomethane per year, which is approximate to 136,622 MMbtu per day. Taking into consideration that the amount of biomethane available in landfills will decrease in those landfills which will no longer be accepting waste in the future or are currently closed, the amount of biomethane from landfills and wastewater treatment plants in the year 2035 will decrease to 737,271 Megagrams per year, which approximates to 89,776 MMbtu per day. Additional biogas feedstocks to consider include anaerobic digester gas from dairy farms and municipal solid waste (MSW). For this work, the potential for RNG produced from these feedstocks in California was obtained from Reference [4]. The report states there is a potential of 90.6 billion cubic feet (bcf) per year of RNG from WWTP, landfills, MSW, and dairy feedstocks; taking into account the current RNG used for power generation and possible recoverable, the actual availability is approximately 57 bcf per year. An additional pathway for the production of renewable synthetic natural gas (RSNG) includes the gasification of solid biomass feedstock located within the State. To estimate the potential RSNG, results from Reference [5] were assumed for solid biomass feedstocks including those from forestry, agricultural waste, and urban activities such as urban green clippings, forest product residue, agricultural residues. From this source, the potential of RSNG that can be produced from solid biomass sources is 675,785 MMbtu per day, which is the by far the largest potential for biomethane relative to the other considered sources. Table 6 displays the resource estimates estimated to be available for use as a HDV fuel.



(a) (b)

(c) (d)

Figure 10. (a) Agriculture biomass in CA in bone dry ton (BDT) per year. (b) Estimate of forest biomass residue in CA in BDT per year. (c) Currently available biomethane in CA from landfills in megagrams (Mg) of Methane per year. (d) Currently available biomethane in CA from wastewater treatment plants in Mg of Methane per year.

Table 6. Daily availability of RNG and RSNG estimated to be available for HDV and MDV fuel

	Reference 1 [3]	Reference 2 [4]	Reference 3 [5]
Fuel	**[MJ/day]**	**[MJ/day]**	**[MJ/day]**
WWTP RNG	**27,140,931**	**5,274,147**	**--**
LFG RNG	**78,350,936**	**97,571,729**	**--**
MSW AD RNG	**--**	**21,096,590**	**--**
Dairy AD RNG	**--**	**26,370,737**	**--**
Biomass RSNG	**--**	**--**	**712,990,759**

Greenhouse Gas Emissions

To estimate the impact on GHG emissions from using RNG and RSNG pathways to provide CNG for MDV and HDV fueling, fuel consumption determined by Vision for each scenario, estimated available fuel volumes per day, and carbon intensity values for each fuel are used to quantify the upstream emissions (i.e., well-to-tank) for each fuel consumed, and then combined with tail pipe emissions (i.e., tank-to-wheel) of CO_2 and CH_4 reported by VISION.

The carbon intensity of RNG is highly dependent on the feedstock. Apart from the carbon intensity of RSNG, all other carbon intensities listed in

Table 7 are derived from fuels which are produced by California sources and are listed under the California Air Resources Board Low Carbon Fuel Standard [17]. When comparing the carbon intensities for each feedstocks, the use of RNG derived from anaerobic digestion of dairy manure achieves the most significant benefit with a well-to-wheel (WTW) value of -276.2 g CO_2e per MJ. Assuming the tank-to-wheel (TTW) emissions would be the same as those in

Table 7, the well-to-tank (WTT) emissions are -333.54 grams of CO_2e per MJ, representing the lowest carbon intensity for the production of RNG. RNG produced from anaerobic digestion of MSW also achieves an overall negative value of -22.9 CO_2e per MJ. RNG from WWTP sources results is assumed to have a value of 19.3 CO_2e per MJ. Landfill RNG has the highest carbon intensity of considered RNG sources at 46.4 g CO_2e per MJ, but still results in a reduction from conventional natural gas of 42%.

Table 7. Carbon intensities for currently available low carbon fuels in California. Adapted from References [4, 5, 17]

	Well-to-Tank [g of CO_2e per MJ]	Tank-to-Wheel [g of CO_2e per MJ]	Well-to-Wheel [g of CO_2e per MJ]
Conventional CNG	22.2	57.3	79.5
Conventional Diesel	27.9	74.9	102.8
Landfill Gas RNG	-11.3	57.3	46.4
Anaerobic Digester Gas from WWTP RNG	-37.9	57.3	19.3
Anaerobic Digester Gas from Dairy RNG	-333.5	57.3	-276.2
Anaerobic Digester Gas from MSW* RNG	-80.2	57.3	-22.9
RSNG from Biomass**	20.3	0	20.3
CA Mix Electricity	105.2	0	105.2
H_2 Produced in CA	47.7	0	47.7

*Municipal Solid Waste, **Renewable Synthetic Natural Gas

Determining the carbon intensity for the RSNG resources is less clear than the other sources of biomethane. Gasification technologies are less commercially mature than other pathways considered here, and an appropriate carbon intensity value from the LCFS was not available. The carbon intensity of RSNG is calculated using the total GHG emissions from the production of potential RSNG as listed in Reference [5]. The production of 839,785 MMBtu of RSNG per day emits a total of 18,000 tons of CO_2e missions per day [5]. From these values, a carbon intensity of 20.32 grams of CO_2e per MJ is calculated for the WTT emissions of RSNG. For this pathway, direct tail pipe emissions estimated in VISION are not included in total GHG calculations. This is because no emissions off-set credit is considered from emissions that would otherwise be released during normal treatment (as is done in CA-GREET 2.0 for the other fuels [18]). Thus, in contrast to the values from the LCFS, RSNG TTW emissions are assumed to be 0 grams of CO_2e per MJ and the resulting wells-to-wheel value is assumed to be 20.32 grams of CO_2e per MJ. This value is reasonably comparable to some fuel pathways within the CA-GREET model for forestry residue. For example, spark ignition vehicles operating on renewable gasoline produced from forest residue-based pyrolysis achieve a 66% reduction in GHG from traditional gasoline [18]. Similarly, the use of RSNG here results in a 74% reduction from conventional natural gas. Nevertheless, pyrolysis to gasoline and gasification to CNG are very different processes. It should be noted that RSNG results are dependent on the assumption and different trends would be observed if tail pipe emissions were included – notably that the use of RSNG from gasification achieve only a very small GHG benefit from conventional natural gas (77.6 g CO_2e/MJ vs 79.46 g CO_2e/MJ).

For the scenarios evaluated, the TTW emissions are taken from VISION model output in order to better capture the different vehicle categories evaluated. This is because TTW emissions listed in

Table 7 only account for one type of heavy-duty vehicle with a fuel economy of 4.8 MJ per mile [19]. The VISION model outputs the tons per day emissions of CO_2 and CH_4 for each scenario specific to each MDV and HDV technology type. Taking the global warming potential to be 25 for CH_4 and 1 for CO_2 for a 100-yr period, the daily greenhouse gas emissions can be calculated in ton of CO_2e [20].

Air Quality Modeling

Shifts to advanced CNG engines from diesel and gasoline technologies will impact direct pollutant emissions including NO_x, reactive organic compounds (ROG), particulate matter (PM), carbon monoxide (CO) and oxides of sulfur (SO_x). Such shifts occur quantitatively (in total), spatially (where), temporally (when), and in composition (what); all of which will subsequently influence ambient concentrations of secondary air pollutant species including ozone and $PM_{2.5}$. To evaluate regional AQ impacts in 2035, emissions must be justifiably projected from current levels and spatially and temporally resolved. Further, the formation and fate of secondary air pollutants is governed by complex, non-linear atmospheric processes. For example, relative to petroleum fuel MDV and HDV, shifts to advanced CNG vehicles will incur AQ benefits, including reductions in ozone and $PM_{2.5}$, due to significant reductions in NO_x. However, without atmospheric modeling quantification of ozone concentration reductions as a result of NO_x emission reductions is not possible. Furthermore, the spatial locations and temporal periods of ground-level ozone concentration changes cannot be determined. Finally, how these impacts might be different in the future given the significant change in emissions and emission sources expected to the year 2035 is unclear. Thus, an in-depth understanding must be obtained regarding emissions from all relevant stages followed by simulations of atmospheric chemistry and transport to properly evaluate AQ and GHG impacts of advanced CNG engines.

Pollutant Emissions

Baseline AQ is established in the year 2035 by projecting emission changes for all end-use scenarios associated with expected technological, energy, and economic trends via data for all energy end-use sectors from the California Air Resources Board's CEPAM: 2016 SIP - Standard Emission Tool [21]. For example, Figure 11 shows normalized growth in NO_x from several major stationary fuel combustion sources from 2012 to 2035 including electric utilities, cogeneration, manufacturing and industrial, oil and gas production, service/commercial, petroleum refining, and food and agriculture. The base year inventory used for this work is the 2012 California Air Resources Board (CARB) emissions inventory. By applying the estimated factor to the 2012 ARB inventory, emissions are grown to the 2035 accounting for expected growth in demand, current and future regulations, etc. Thus, the ratio of the 2035 emissions relative to the 2012 emissions for six key air pollutants (NO_x, ROG, $PM_{2.5}$, PM_{10}, SO_2, CO) can be used to determine the absolute value of emissions in 2035.

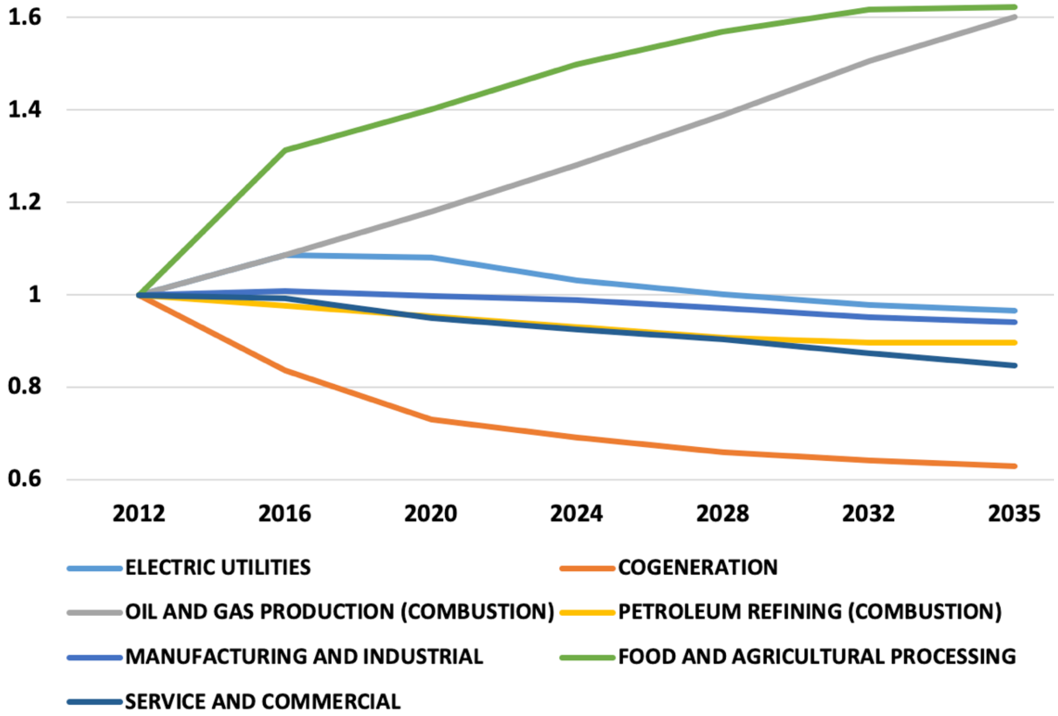


Figure 11. Normalized NO_x emissions from stationary fuel combustion in California. From Reference [21].

The CEPAM data is used for all emission sources in California with the exception of direct MDV and HDV emissions which are obtained from the VISION model scenarios described previously. For each scenario run, Vision outputs total emissions in 2035 from HDV and MDV of criteria pollutants including NO_x, PM in both 10 ug (PM_{10}) and 2.5 ug size ($PM_{2.5}$), ROG, and CO. Additionally, Vision outputs tailpipe emissions of GHG including CO_2 and CH_4. With similarity to the CEPAM method application, the 2012 emissions from Vision are compared with the projected 2035 emissions to develop projection factors for HDV and MDV. Tail pipe emissions of criteria pollutant from advanced HDV relative to diesel and gasoline equivalent vehicles calculated from the Base Case fleet mix are shown in Table 8. As can be seen, the use of advanced engines reduces emissions of NO_x by 96% from baseline diesel and 93% from diesel engines assumed to meet the EPA GHG 2 standards. Relative to an advanced low-NO_x diesel engine, advanced CNG engines can reduce NOx by 20%. Advanced CNG engines can also reduce emissions of ROG from both baseline and advanced diesel and gasoline engines. $PM_{2.5}$ emissions are more similar between all technologies because emissions of PM2.5 generated through brake and tire wear are irrespective of engine technology and fuel. **It should be noted that upstream pollutant emissions for vehicle fueling pathways are not considered in AQ**

assessment and pollutant emission changes are considered only for direct vehicle tailpipe and evaporative emissions. Conversely, carbon intensity calculations for GHG assessment account for the life cycle (WTW) emissions of utilized fuel and technology pathways.

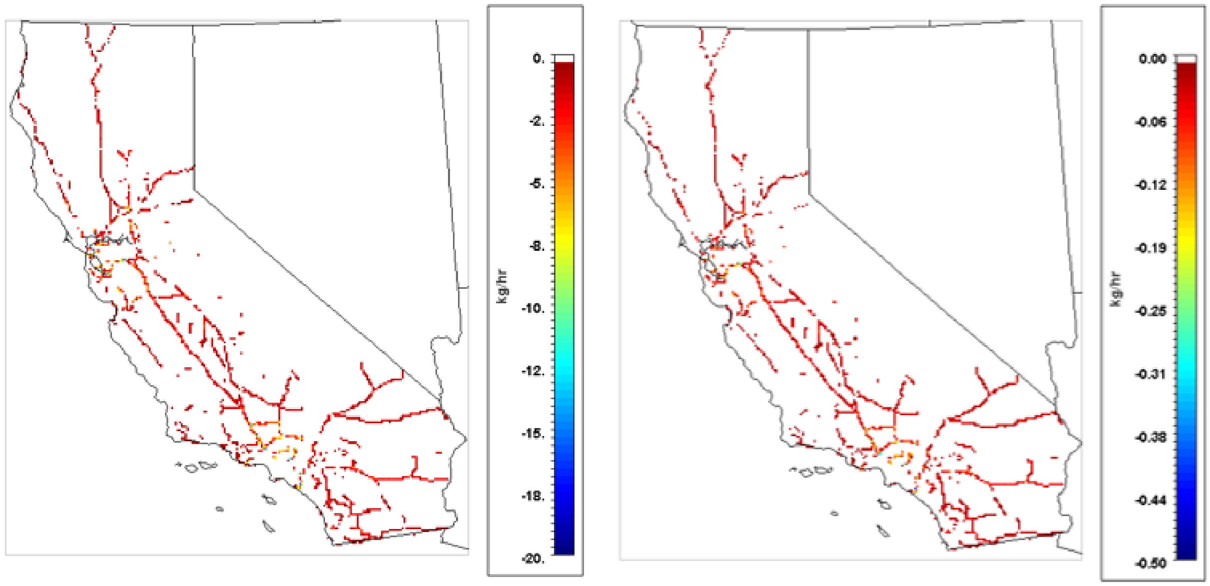
Table 8. Direct emissions for advanced CNG, diesel, and gasoline vehicles estimated from the SIP in 2035

Vehicle	**NO_x [g/mile]**	**ROG [g/mile]**	**$PM_{2.5}$ [g/mile]**	**CO [g/mile]**
Advanced CNG	0.107	0.053	0.055	0.692
Diesel (Baseline)	2.550	0.084	0.055	0.474
Diesel (EPA GHG 2)	1.663	0.111	0.052	0.901
Diesel (SIP)	0.134	0.064	0.048	0.267
Gasoline (Baseline)	0.926	0.762	0.048	4.383
Gasoline (SIP)	0.038	0.120	0.049	2.266

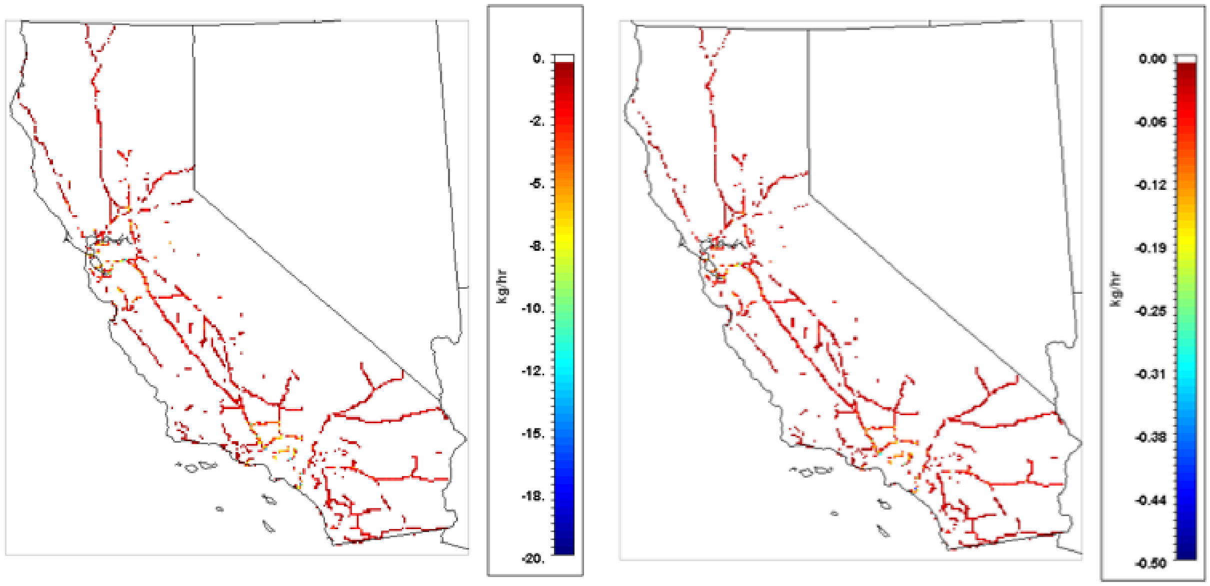
Next, emission changes representative of each scenario are utilized in the development of spatially and temporally resolved emission fields required as input in AQ modeling. The factors utilized to grow and control emissions to 2035 are applied and simultaneously spatially and temporally resolved using the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system [22]. SMOKE accounts for geospatial (e.g., truck activity, routes, etc.) and temporal (e.g., drive patterns, times, etc.) information associated with MDV and HDV activity in California. This is achieved through source- and pollutant-specific source classification codes to manipulate the 2012 ARB inventory in this work to the year 2035 while simultaneously resolving emissions spatially and temporally within California.

Output files from SMOKE provide insight into emission reductions including quantitative changes in total emissions and the spatial locations of changes. For example, differences achieved from the Base Case in Case 1B in spatial and temporal emissions of NO_x and $PM_{2.5}$ in

summer are shown in Figure 12 (a) and (b), respectively. As would be expected, reductions are visible from transportation networks within California including the locations of vehicle activity i.e., local roadways, highways, interstates. The output of SMOKE is gridded in 4 km x 4 km cells with peak reductions associated with Case 1B exceeding -26 kilograms NO$_X$ per hour (kg/hr) and -0.5 kg/hr PM$_{2.5}$. Locations of peak emission reductions occur in regions of urban areas supporting high levels of MDV and HDV activity including the South Coast Air Basin (SoCAB) and the San Francisco (S.F.) Bay area. While these results are presented as the maximum 24-hour average difference, SMOKE calculates the hourly difference which allows for temporal driving patterns, e.g., weekday vs. weekend, diurnal drive cycles.



(a) **(b)**



(a) **(b)**

Figure 12. Δ Maximum 24-hour average emissions attained in the Summer 1B Case from the Base Case for (a) NO_x and (b) $PM_{2.5}$

Atmospheric Modeling

Simulations of atmospheric chemistry and transport are accomplished via the Community Multi-scale Air Quality model (CMAQ) version 4.7, with the Carbon Bond 05 chemical mechanism to establish fully developed distributions of atmospheric concentrations of pollutants of interest, including ground-level ozone and $PM_{2.5}$ [23]. CMAQ is a comprehensive AQ modeling system developed by the US Environmental Protection Agency (EPA) and widely used for a numerous AQ assessment needs [24]. The source code and technical formulation for CMAQ are available at: www.cmaq-model.org. CMAQ is designed from a "one atmosphere" perspective and has been used extensively in research into tropospheric ozone, PM, acid deposition and visibility [25]. CMAQ includes meteorological modeling, emissions modeling and chemical transport modeling systems. Required inputs include meteorological conditions, initial and boundary conditions, land use and land cover information, and anthropogenic and biogenic source emissions. The chemical mechanism used is the CB05, accounting for the photochemical formation of ozone, oxidation of ROG and formation of organic aerosol precursors. The spatial resolution of control volumes is 4 km × 4 km, and a vertical height of 10,000 meters above ground, with 30 layers of variable height based on pressure distribution. Meteorological input data was acquired from the Advanced Research Weather Research and Forecasting Model, WRF-ARW.

For the 2035 advanced CNG cases, two simulation periods are conducted to capture the effect of seasonal variation in meteorology and emissions on ozone and $PM_{2.5}$ concentrations including a summer episode (July 8-21, 2005) and winter episode (January 1-14, 2005). July is selected as this period encompasses conditions typically associated with high tropospheric ozone formation, including high temperatures, an abundance of sunlight, lack of natural scavengers, and the presence of inversion layers [26]. The January period also is associated with high levels of $PM_{2.5}$ in some regions of California, including the South Coast Air Basin (SoCAB). The winter modeling period is added to explore impacts during periods of high $PM_{2.5}$ in other areas of California, including the San Joaquin Valley. Ground-level concentrations are obtained from the final day of simulation (July 21 and January 14) and used to determine baseline and delta maximum 8-hour average values for ozone and 24-hour average values for $PM_{2.5}$.

Results

Greenhouse Gas Emissions

By switching natural gas feedstock from conventional fossil to a renewable fuel, reductions in GHG emissions will be achieved. Different feedstock sources will have a dissimilar impact as each is associated with a unique carbon intensity. However, each of the renewable feedstock analyzed in this work is also limited in availability, and may not be able to meet the total demand for fuel estimated for a given scenario. In this work, different scenarios for feedstock mixes are considered for the production of biomethane in order to establish spanning estimates of potential GHG impacts. It must be considered that the assumption here that all biogas and biomass resources for each resource category are utilized for HDV and MDV is unlikely to occur given competing demands from other sectors, and the results in the following section present an upper bound for potential impacts.

The WTT carbon intensity for each feedstock is listed in

Table 7 and is used to find the upstream GHG emissions for each scenario taking into consideration the different feedstock mixes. The total WTW GHG emissions for the Cases considered are composed of WTT emissions and TTW emissions. While the WTW emissions are calculated using carbon intensities, the TTW emissions are taken from the VISION model which is able to take into consideration the different types of vehicle categories and efficiencies at which they operate under. For those scenarios that have diesel and gasoline vehicles, the diesel and gasoline fuel demand is assumed to be derived from fossil feedstock. For those cases which include electric and hydrogen vehicles, the fuel feedstock considered for electricity is the California electricity mix and for hydrogen is the cracking of methane derived from a mixture of landfill gas (33%) and North American fossil natural gas.

RNG from WWTP and landfills is more easily available than RNG from other sources, and represents the bulk of currently available RNG. Contrastingly, RNG from MSW and dairies will require additional technical advancement prior to widespread utilization, e.g., the construction of digesters and established infrastructure. Similarly, RSNG from biomass gasification represents a pathway that is not currently commercial. Due to the uncertainty associated with biomass and biogas resources including technical, economic, and sociopolitical factors, a range of possible resource category mixes are considered to estimate GHG impacts. It should be noted that the assumed mixes of resources are not directly comparable due to different assumptions of resource availability and the selection of different fuel production pathways which have different technical availabilities, efficiencies, etc. Rather the two resource mixes are made to provide general insights into the GHG impacts associated with different biomethane pathways. These mixes can be separated into two general categories as follows:

(1) First, estimates of RNG from WWTP and landfills from Reference [3] are considered both with and without the presence of RSNG from biomass gasification from Reference [5].
(2) Second, estimates of RNG from WWTP, landfills, dairies, and MSW from Reference [4] are considered without the availability of RSNG

Resource Mix 1

The first set of scenarios for feedstock mix includes landfill gas, anaerobic digester gas from WWTP, and conventional fossil natural gas as these represent the most likely near-term fuel supply mixes. Additionally, RSNG from biomass is included to compare the impacts associated with solid biomass relative to biogas. The feedstock mixes for the first set of considered resources are listed in Table 9.

Table 9. Description of feedstock mixes considered for the analysis of GHG emissions for Resource Mix 1

Natural Gas Feedstock Mixes	Feedstock Mix Description
All Conventional	All diesel, gasoline, and natural gas fuels are derived from conventional fossil fuel feedstock
Use of LFG+ADG+BioM+Conv	Natural gas fuel demand is first met by RNG derived from landfill gas (LFG), anaerobic digester gas (ADG) from WWTP, and biomass (BioM) feedstock, in that order. Afterwards, any other natural gas demand is met by fuels derived from conventional fossil fuel feedstock
Use of LFG+ADG+Conv	Natural gas fuel demand is first met by RNG derived from LFG and ADG from WWTP, in that order. Afterwards, any other natural gas demand is met by fuels derived from conventional fossil fuel feedstock

Assuming all possible RNG and RSNG is utilized for Resource Mix 1 (i.e., the LFG+ADG+BioM+Conv Case), Table 10 provides the fractions of demand met by each biomethane source for each scenario considered given the estimated resource availabilities, the assumed resource utilization order (LFG, then ADG from WWTP, then RSNG from biomass, and then conventional natural gas) and total CNG demand. In the Base Case, demand for CNG is very small and thus 100% of the total demand is met with LFG. Case 1B has the highest demand for CNG, and requires an additional 35% of CNG demand to be met with conventional fossil natural gas after RNG and RSNG resources are utilized. Similarly, Case 2B requires 22% of CNG demand be met with fossil resources. Conversely, Case 2B has a lower demand for CNG and is able to meet total demand with RNG and RSNG and does not require fossil natural gas. Given the significantly higher total availability, RSNG meets the largest fraction of CNG in all Cases, with LFG meeting the next highest and ADG from WWTP providing the smallest portion. It should again be noted that the assumption that all available feedstock is available to provide fuel for HDV and MDV is highly optimistic. Further, no assumption is made regarding several important aspects of the WTT life cycle including the refinement and transportation of fuel to fueling stations. Therefore, these results provide an approximation of the potential GHG impacts.

Table 10. Percent breakdown of natural gas demand met when considering landfill gas, anaerobic digester gas form WWTP, RSNG from biomass and conventional feedstock for the production of natural gas in the Base Case and alternative Cases.

Case	Conventional	Landfill Gas	ADG from WWTP	RSNG from Biomass
Baseline	0 %	100 %	0 %	0 %
1B	35 %	6 %	2 %	56%
2B	22 %	7 %	2 %	67 %
3B	5 %	9 %	3 %	82 %
4B	0 %	11 %	4 %	84 %

Figure 13 displays the WTWs GHG emissions for the Base Case and alternative cases derived from the Base Case. The values include emissions for all vehicle types and fuels including diesel, gasoline, and natural gas (the Base Case does not assume electric or hydrogen vehicle deployment). In the Base Case, a small amount of vehicles are assumed to be CNG and substituting the corresponding amount of CNG from conventional natural gas to RNG thus results in a minor GHG reduction. Relative to the Base Case, reductions in GHG range from 14 to 26% assuming all CNG is of fossil origin to 42% to 62% assuming both RNG and RSNG are available to meet demand. Reductions in GHG emissions occur even when fossil natural gas is used entirely for CNG demand as a result of efficiency increases for all the technologies available by 2035 and the reduction of diesel fuel consumption which has a higher carbon intensity than fossil CNG. This is also evident as GHG emission reductions scale across cases with the displacement of diesel fuel, e.g., Case 1B has the lowest WTW GHG emissions of alternative cases at 72,480 metric tons of CO_2e per day when considering the use of all renewable sources. Contrastingly, Case 4B has the lowest overall displacement of diesel and gasoline fuel with CNG, and therefore is associated with the highest GHG emissions of 109,384 metric tons of CO_2e per day for the same renewable CNG assumption. Amongst alternative Cases, the significant difference in resource availability is evident when considering the inclusion of RSNG in overall GHG results. Notably, the amount of LFG and AD from WWTP estimated for vehicle fueling is small relative to the amount estimated for RSNG. For example, relative to using fossil CNG alone, including in-state LFG and AD from WWTP only achieves a small reduction in total GHG emissions as combined those resources meet only a minor portion of total CNG demand, e.g., for Case 1B both sources together provide approximately 8% of demand. Conversely, RSNG can meet 56 to 84% of CNG demand. Shown in Table 10, when considering the percentage of fuel demand which can be met by LFG, ADG and RSNG, only in Case 4A is the entirety of CNG demand met by renewable feedstock. For the other cases, at least 5% of utilized CNG is assumed to come from fossil natural gas in order to meet total demand. Therefore, the use of LFG, ADG, and RSNG combined with conventional natural gas to meet the demand for the MDV and HDV sector has the lowest GHG emissions for all alternative cases due to the significantly higher total availability of renewable CNG.

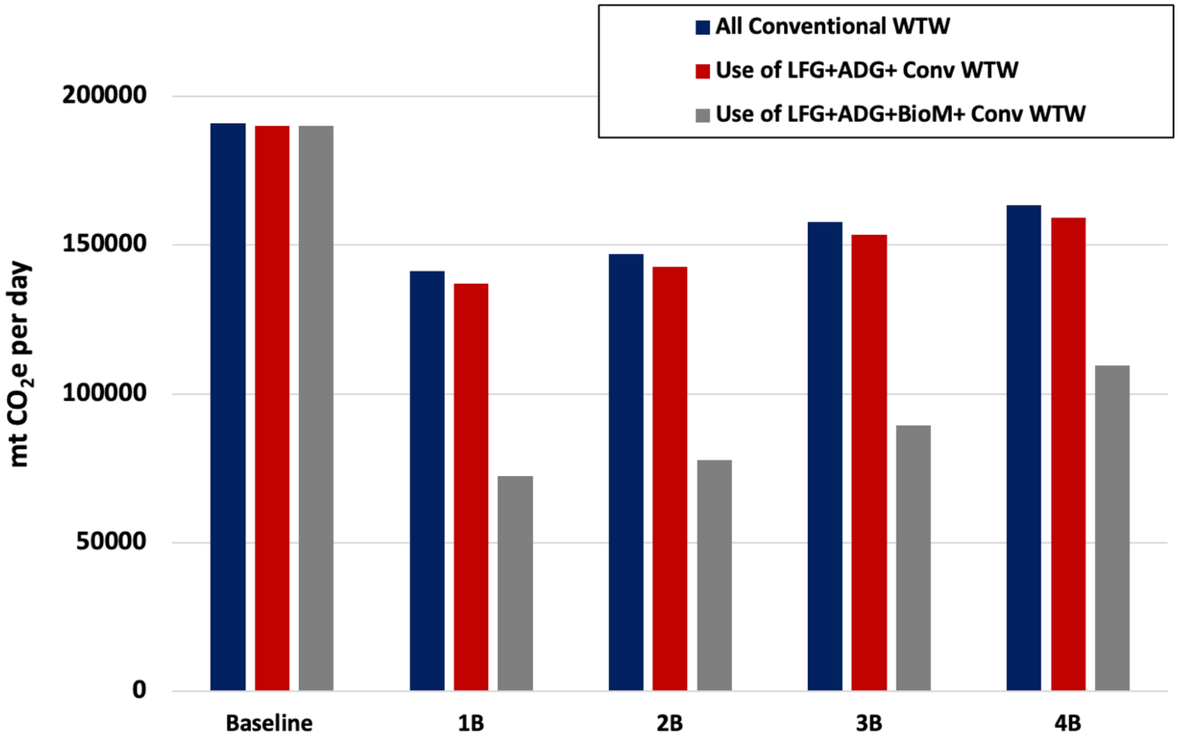


Figure 13. Well-to-wheels GHG emissions for the Base Case and alternative cases derived from the Base Case for Resource Mix 1

Table 11 provides the fractions of demand met by each biomethane source for each scenario considered given the estimated resource availabilities, the assumed resource utilization order and total CNG demand for the SIP Case and derived alternative Cases. Due to the assumed implementation of additional low-emitting technologies including hydrogen and electricity which results in a lower overall demand for CNG, all Cases are able to meet total CNG with renewable CNG with the exception of Case 2A. In the SIP Case LFG and ADG together can provide 85% of estimated demand with RSNG providing an additional 14%. Similarly, CNG demand for Case 2C could be met with 15% LFG, 5% ADG from WWTP, and 79% from RSNG. Case 2A assumes 100% penetration in HDV which results in a significantly higher demand for CNG than the other Cases and requires 22% of total demand be met by conventional fossil natural gas.

Table 11. Percent breakdown of natural gas demand met when considering landfill gas, anaerobic digester gas form WWTP, RSNG from biomass and conventional feedstock for the production of natural gas in the SIP Case and alternative Cases.

Case	Conventional	Landfill Gas	ADG from WWTP	RSNG from Biomass
SIP	0 %	63 %	22%	14 %
2A	22 %	7 %	2%	67 %
2C	0 %	15 %	5 %	79 %
2D	0 %	13 %	4 %	81 %
3A	0 %	10 %	3 %	86 %
4A	0 %	14 %	5 %	80 %

Figure 14 displays the WTWs GHG emissions for the Base Case, the SIP Case and alternative cases derived from the SIP Case. The values for the SIP Case and alternative SIP Cases include emissions for all vehicle types and fuels including diesel, gasoline, CNG, electric and hydrogen vehicles. The cleaner technologies and fuels assumed for the SIP Case result in an 18 to 21% reduction in GHG from the Base Case depending on the source of CNG. For the SIP Case, a higher percentage of vehicles is assumed to be CNG than in the Base Case and therefore, substituting the corresponding amount of CNG from fossil natural gas to RNG and RSNG has a bigger impact (although still moderate overall). Relative to the SIP Case, reductions in alternative SIP Cases range from 6 to 9% assuming all CNG is of fossil origin, 9 to 11% assuming LFG and AD from WWTP is available, and 34 to 53% assuming LFG, AD from WWTP and RSNG is available to meet CNG demand. As all cases are able to meet total CNG demand with RNG and RSNG with the exception of Case 2A, results scale with total diesel and gasoline displacement. For example, Case 2A achieves the largest reduction in GHG as a higher amount of diesel and gasoline is offset from the assumed 100% penetration of HDV. Similarly, Case 3A achieves the second highest reduction due to the assumed 100% penetration of MDV.

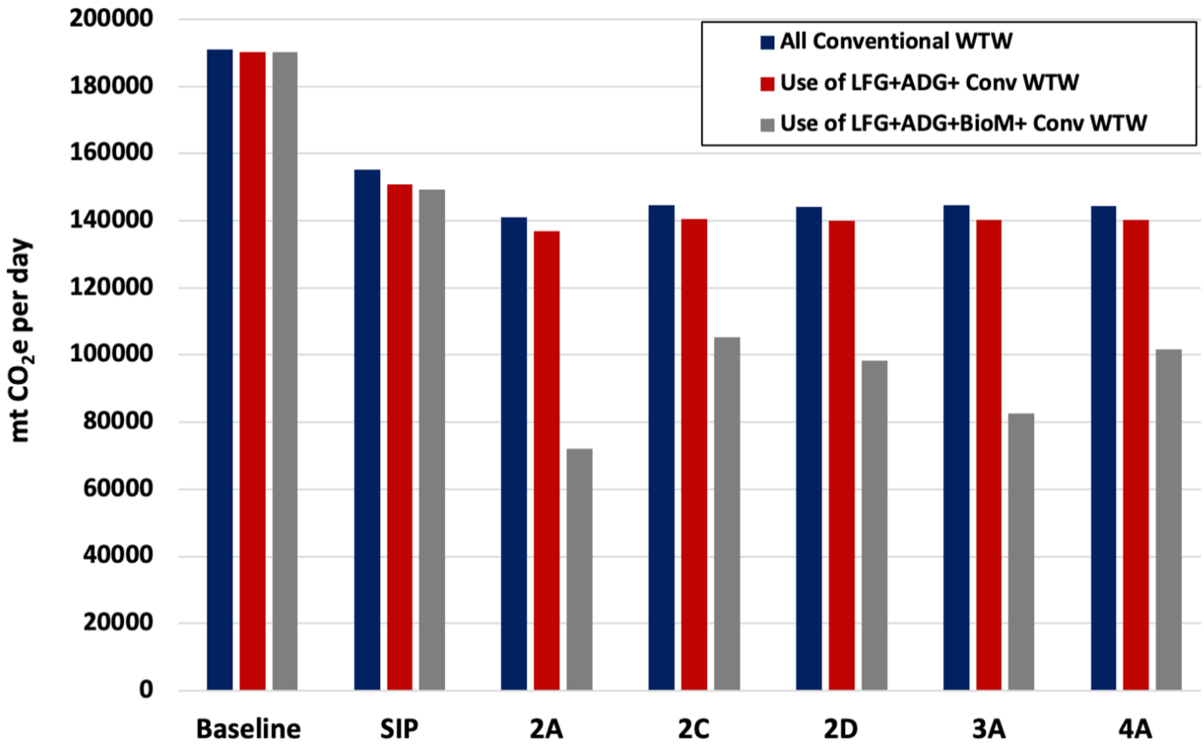


Figure 14. Well-to-wheels GHG emissions for the Base Case, SIP Case and alternative cases derived from the SIP Case for Resource Mix 1

Resource Mix 2

The second resource mix also includes LFG and ADG from WWTP but also includes biomethane from the anaerobic digestion of dairy manure and MSW (i.e., LFG+ADG+Dairy+ MSW+ Conv). Resource Mix 2 provides an upper bound of the potential for RNG derived fuels as RSNG from the gasification of biomass is not considered. As described previously, between LFG, ADG from WWTP, dairy ADG, and MSW ADG there is a total potential of 57 bcf per year of RNG available in California [4]. Table 12 displays the Percent of natural gas demand met when considering LFG, ADG from WWTP, ADG from dairy farms, ADG from MSW, and conventional natural gas. Based upon the current feasibility of resources, it is assumed that LFG is utilized first, ADG from WWTP is utilized next, ADG from dairies follows, and ADG from MSW is utilized last. In reality, the mix of resources providing RNG would not be dispatched as such and would be a represented by a mix of all sources irrespective of the remaining potential within each resource category. However, the Baseline and SIP Cases are the only cases impacted by the dispatch order as the others utilized all estimated resource potential within a given resource category. For all alternative Cases considered, the majority of CNG is provided from fossil natural gas (i.e., 70 to 88%) due to the limited amount of RNG available in-state. Case 2C has the lowest CNG demand and thus RNG from all sources is able to provide approximately 30% of total demand. Conversely, Case 1B has the highest CNG demand and RNG provides about 12% of total demand. Overall, LFG provides the largest amount of RNG within scenarios (7.7 to 14.9%), with ADG from dairies and MSW providing roughly equivalent portions (2.1 to 5.3% and 1.7 to 4.2%).

ADG from WWTP provides only a small portion of total RNG ranging from 0.4 to 1.1%. It should be noted that the amount of ADG from WWTP is significantly lower in Reference [4] than what is reported in Reference [3] for Resource Mix 1 due to different assumptions in resource estimation. This highlights the challenges associated with predicting total available RNG for future years.

Table 12. Percent of natural gas demand met when considering LFG, ADG from WWTP, ADG from dairy farms, ADG from MSW, and conventional feedstock for the production of natural gas for all considered cases.

Case	Conventional	Landfill Gas	ADG from WWTP	Dairy	MSW
Baseline	0 %	100 %	0 %	0 %	0 %
SIP	0 %	79.17 %	4.28 %	16.55 %	0 %
1B	88.16 %	7.68 %	0.42 %	2.08 %	1.66 %
2A	85.77 %	9.24 %	0.50 %	2.50 %	2.00 %
2B	85.81 %	9.21 %	0.50 %	2.49 %	1.99 %
2C	69.97 %	19.49 %	1.05 %	5.27 %	4.21 %
2D	73.70 %	17.07 %	0.92 %	4.61 %	3.69 %
3A	80.02 %	12.97 %	0.70 %	3.51 %	2.80 %
3B	82.60 %	11.29 %	0.61 %	3.05 %	2.44 %
4A	72.11 %	18.10 %	0.98 %	4.89 %	3.91 %
4B	77.00 %	14.93 %	0.81 %	4.04 %	3.23 %

Figure 15 shows the total WTW GHG emissions for the Base Case, SIP Case, and the alternative Cases derived from the Base and SIP Cases. The use of an in-state feedstock mix comprised of LFG, ADG from WWTP, ADG from Dairy, ADG from MSW, and conventional natural gas results in reductions in the Base Case from 22 to 34% and from the SIP Case of 16 to 18%. Results again scale with the penetration of CNG in place of diesel and gasoline. For the Base Case, Case 1B has the lowest GHG emissions with a total of 126,212 metric tons of CO_2e per day while Case 4B has the highest at 148,198 metric tons of CO_2e per day. For the SIP Case, Case 2A has the lowest GHG emissions with a total of 126,042 metric tons of CO_2e per day while Case 3A has the highest at 129,570 metric tons of CO_2e per day. Relative to Resource Mix 1, the results are directly driven by the availability of resources for RNG production. The carbon intensity of dairy ADG and MSW ADG has a much lower WTW value than that of RSNG from biomass, but the limited resource availability prevents reductions from exceeding those attained in the RSNG inclusive scenarios in Resource Mix 1.

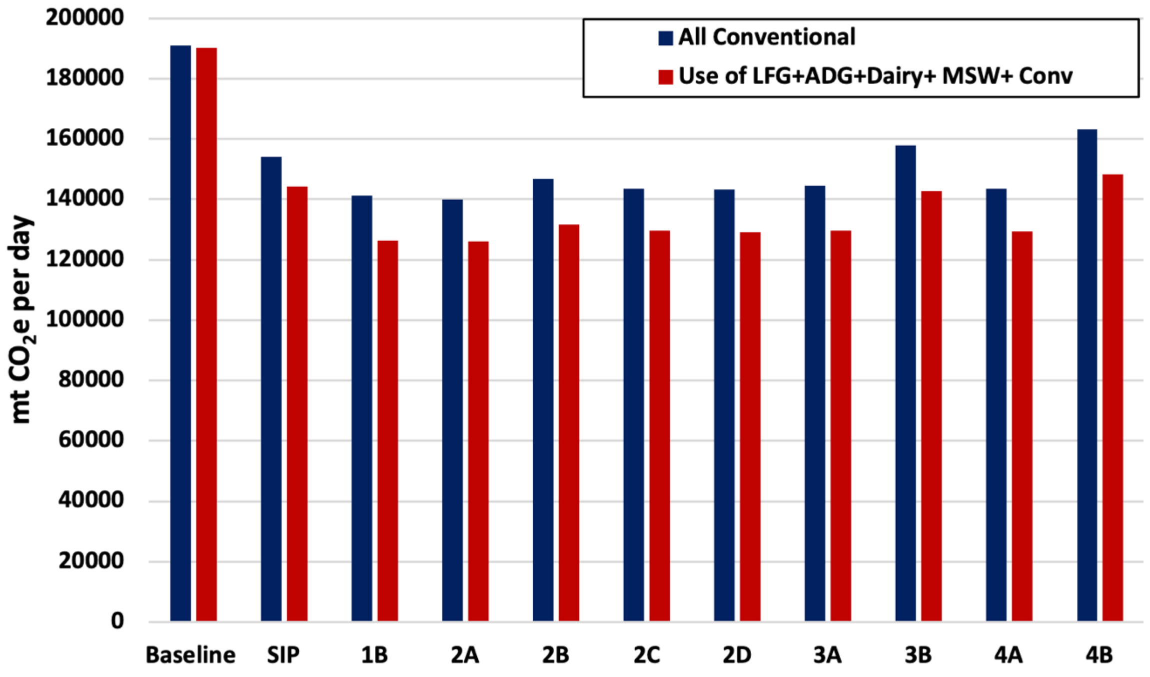


Figure 15. Well-to-wheels GHG emissions for the Base Case, SIP Case and alternative cases derived from the Base and SIP Case for Resource Mix 2

Criteria Pollutant Emissions

Figure 16 shows total vehicle emissions (i.e., tailpipe for NO_x, tailpipe and evaporative for ROG, and tailpipe, tire wear, and brake wear for $PM_{2.5}$) for the Base Case and the alternative cases developed with the Base Case as a starting point. The emissions are summed for HVD and MDV a reported in tons per day (tpd). As would be expected the 100% advanced CNG case achieves the lowest total emissions of NO_x of approximately 14 tpd, representing a 91% reduction from the Base Case. Conversely, the 4B Case (50% advanced CNG in both HDV and MDV) achieves the minimum reduction of 57%. Demonstrating the larger share of emissions attributable to HDV relative to MDV, Case 2B (100% HDV and 50% MDV) achieves a higher reduction than does Case 3B (50% HDV and 100% MDV), i.e., 82% vs. 66%. Emissions of ROG are significantly reduced from the Base Case for all Cases, exceeding 38% and 97% reductions, respectively. However, between Cases small differences in ROG and are estimated. Contrastingly, emissions of $PM_{2.5}$ are minor both between considered Cases and the Base Case, and between the considered Cases. This is likely a result of (1) assumed tail pipe emissions of $PM_{2.5}$ for advanced CNG being principally equivalent to other advanced technologies including diesel and gasoline engines, and (2) emissions of $PM_{2.5}$ generated from tire wear and brake wear will remain relatively constant as they are not a function of engine technology and fuel composition.

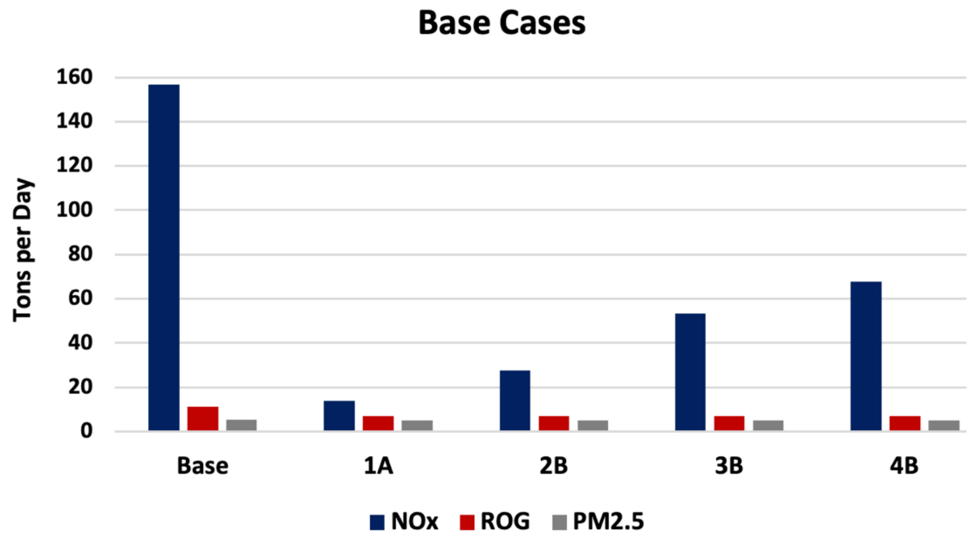


Figure 16. Total HDV and MDV emissions of NO_x, ROG, and $PM_{2.5}$ in 2035 for the Base Case and Alternative Scenarios

Figure 17 shows total HDV and MDV emissions for the SIP Case and the alternative cases developed with the SIP Case as a starting point. In the SIP Case emissions of NO_x are significantly reduced (i.e., 76%) from the Base Case as a result of assumed increases in near- and zero emission technologies. The 1B Case reduces NO_x from the SIP case by 62%, demonstrating the ability of advanced CNG vehicles to further reduce NO_x emissions within an advanced technology portfolio. The 2A Case results in largest reduction outside of Case 1B of 76%, followed by Case 2D (71.4 %), Case 3A (71.1%) and Case 4A (70%). The comparable NO_x reductions between Case 2D and 3A arise as a result of the assumption within Case 2D of all in-state HDV transitioning to advanced CNG, i.e., out of state vehicles remain the baseline technology for the SIP Case. The result is that for Case 2D, 60% of HDV transition to advanced CNG which is close to the 50% penetration assumed in Case 3A. Due to the higher contribution of HDV to total emissions, NO_x emissions in Case 4A are also similar to Case 2D and Case 3A due to the assumed 50% penetration of HDV, despite a difference of assumed penetration within MDV. Case 2C results in a 41% HDV fleet transition and thus attains the lowest achieved reduction in NO_x under the assumption that only in-state vehicles transition to advanced CNG engine technology. As with the Base Case, a reductions between Cases of ROG are minor, but are reduced from the SIP Case, and reductions of $PM_{2.5}$ are not reduced significantly.

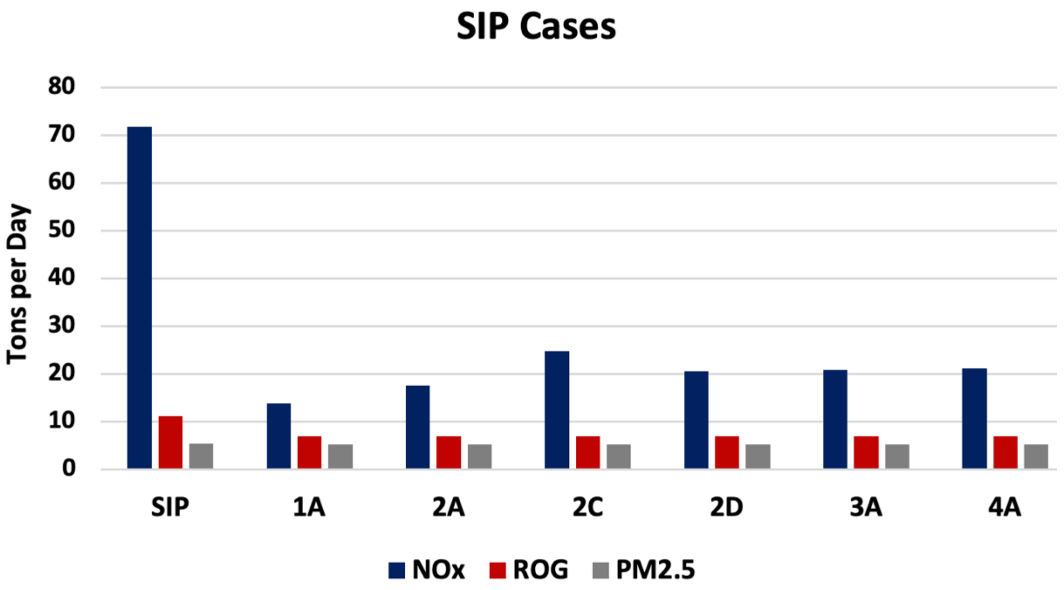


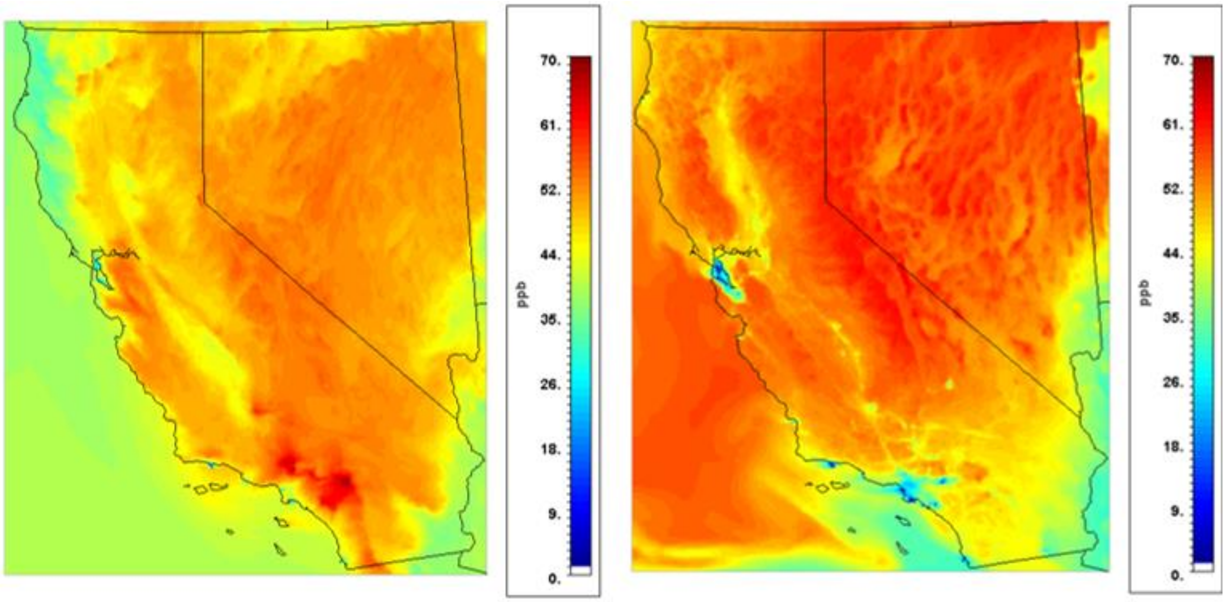
Figure 17. Total HDV and MDV emissions of NO_x, ROG, and $PM_{2.5}$ in 2035 for the SIP Case and Alternative Scenarios

Air Quality Results

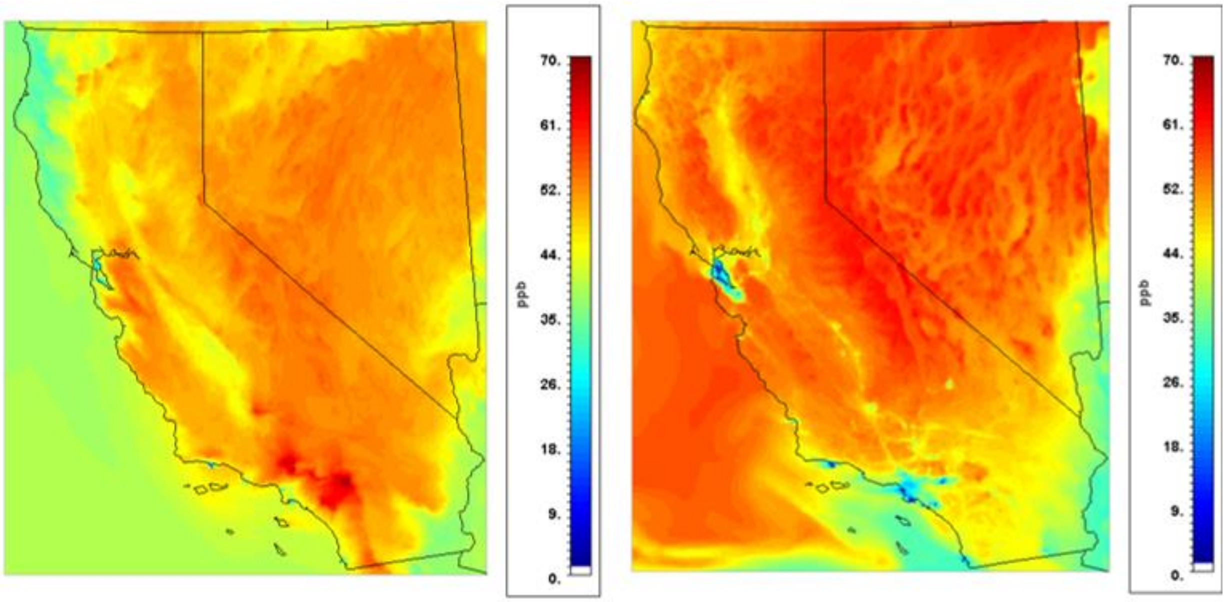
The following sections provide results from the AQ modeling for the alternative scenarios considered. Baseline levels of atmospheric pollutant concentrations are predicted by CMAQ through the Base and SIP Cases. Changes in concentration predicted by CMAQ for alternative cases occur as a result of pollutant emission changes driven by advanced CNG MDV and HDV deployment. Differences in ozone are reported as maximum 8-hour average and 24-hour average is used for $PM_{2.5}$. For each case, results are provided as difference plots for ozone and $PM_{2.5}$ in summer, and $PM_{2.5}$ in winter.

Base Case

In the Base Case, simulated ground-level concentrations of ozone reach 68 ppb in maximum 8-hour average (shown in Figure 18a) and 78 ppb in maximum 1-hour average. Peak levels occur in regions downwind of major urban areas including the SoCAB, the S.F. Bay Area, the Central Valley, and the Greater Sacramento area. Ground-level concentrations of ozone in the Winter Base Case peak at 63 ppb maximum 8-hour average (Shown in

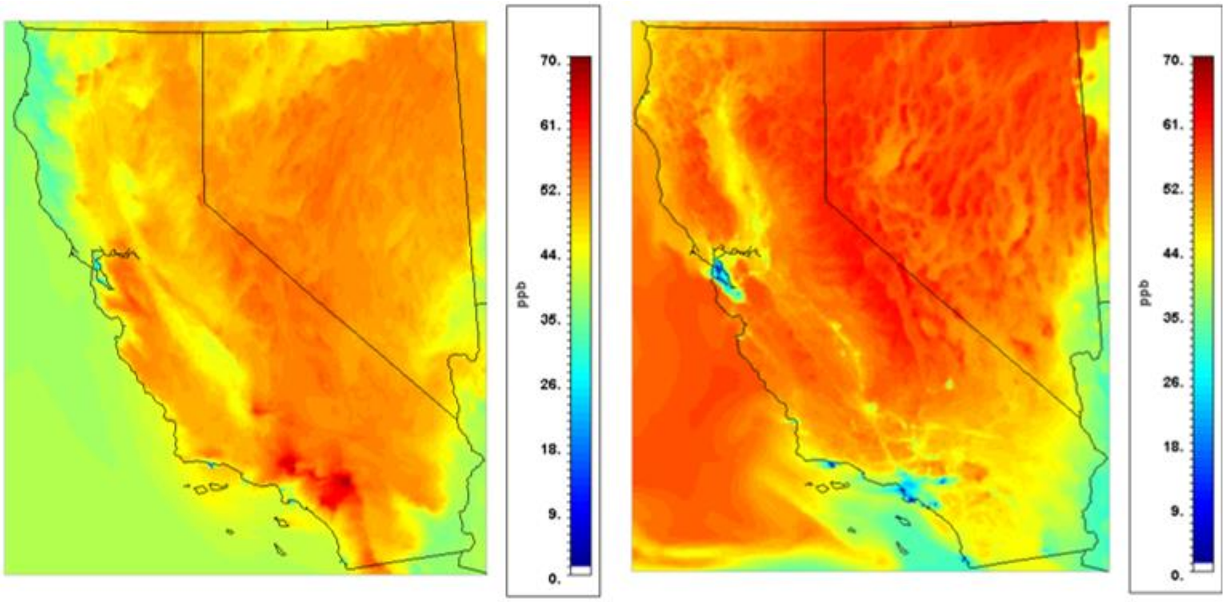


(a) **(b)**



(a) **(b)**

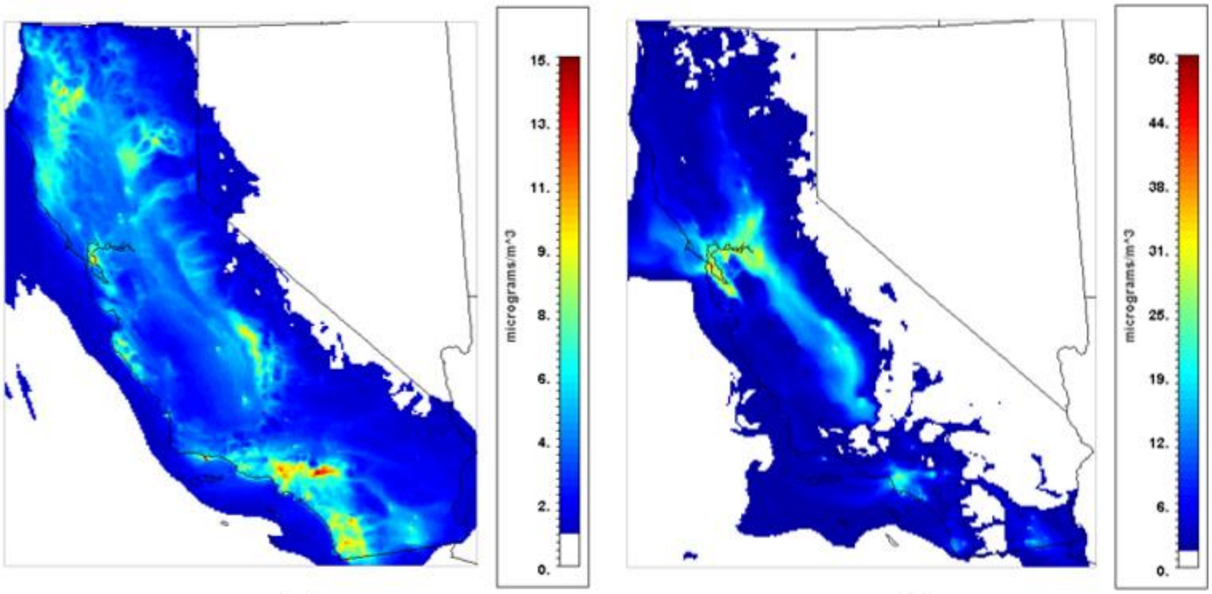
Figure 18b) and 63 ppb maximum 1-hour average. Ozone concentrations in winter follow a reverse trend that in summer, i.e., urban areas have the lowest concentrations while concentrations peak in rural areas.



(a) (b)

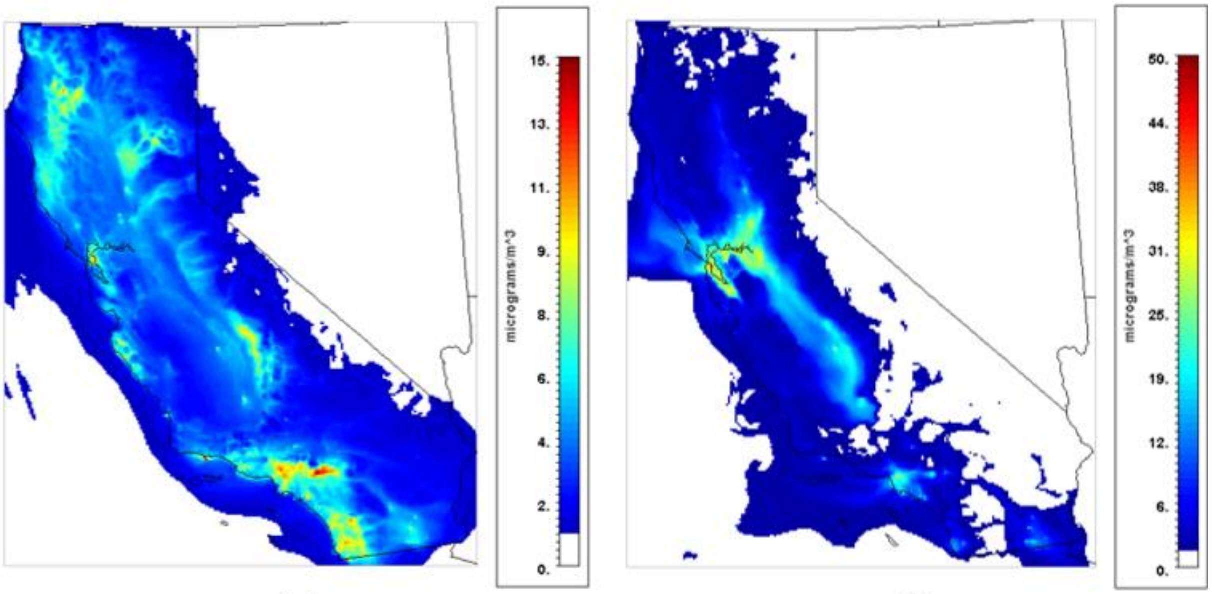
Figure 18. Ambient max 8-hr average ozone in the Base Case for (a) Summer and (b) Winter

Modeling episodes seasonally is necessary to comprehensively determine the impact of HDV and MDV emission changes on ground-level ozone. For example, ozone levels peak in the summer months as high ambient temperatures are favorable for the atmospheric chemical reactions driving ozone formation [27]. Contrastingly, ozone concentrations in winter in California are typically low and generally below Federal NAAQS, e.g., predicted levels for the Base and SIP Cases remain under the Federal NAAQs for maximum 8-hour (70 parts per billion (ppb)) and California standards for maximum 8-hour (70 ppb) and maximum 1-hour (90 ppb). Furthermore, the dynamics of winter ozone in California generally result in impacts from titration, i.e., increases in NO_x emissions yield localized increases in ozone due to reduced scavenging. Therefore, ozone is not reported for the winter episode because background levels of ozone in winter are not of concern for human health.



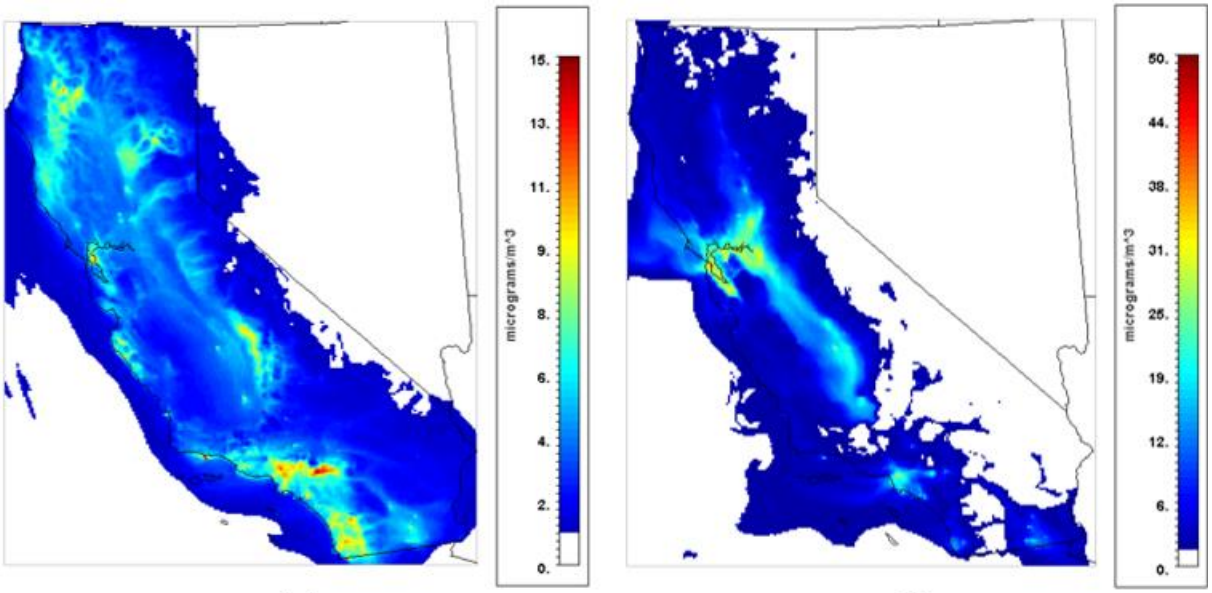
(a) (b)

Figure 19 shows the predicted 24-hr average PM$_{2.5}$ for the summer (



(a) (b)

Figure 19a) and winter (



(a)

(b)

Figure 19b) cases in 2035. For the summer episode, concentrations reach 17.8 ug/m^3 with peak impacts located in areas of the SoCAB. Additional areas experiencing high levels include San Diego County, parts of the Central Valley, the Sacramento Valley, and the S.F. Bay Area. Concentrations are significantly higher in the winter episode at 46.07 ug/m^3, but impacts differ spatially from the summer results, e.g., the S.F. Bay Area and different areas of the Central Valley experience the highest concentrations. Results highlight the seasonal variation of PM$_{2.5}$. Within the Central Valley the peak levels of PM$_{2.5}$ occur in winter months, although concentrations remain above NAAQS and remain of concern in summer and fall[6]. Contrastingly, the highest levels within the SoCAB are reached in summer months. Thus, impacts of alternative MDV and HDV technology-driven emission changes differ depending on region and season and must be considered spatially and seasonally for thorough assessment.

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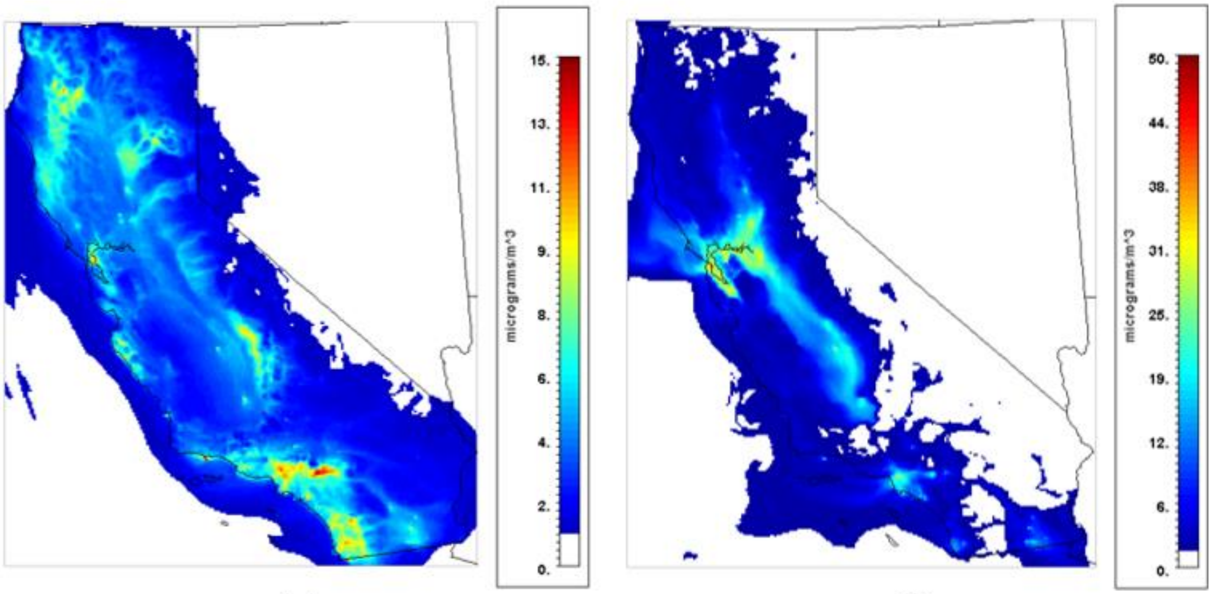
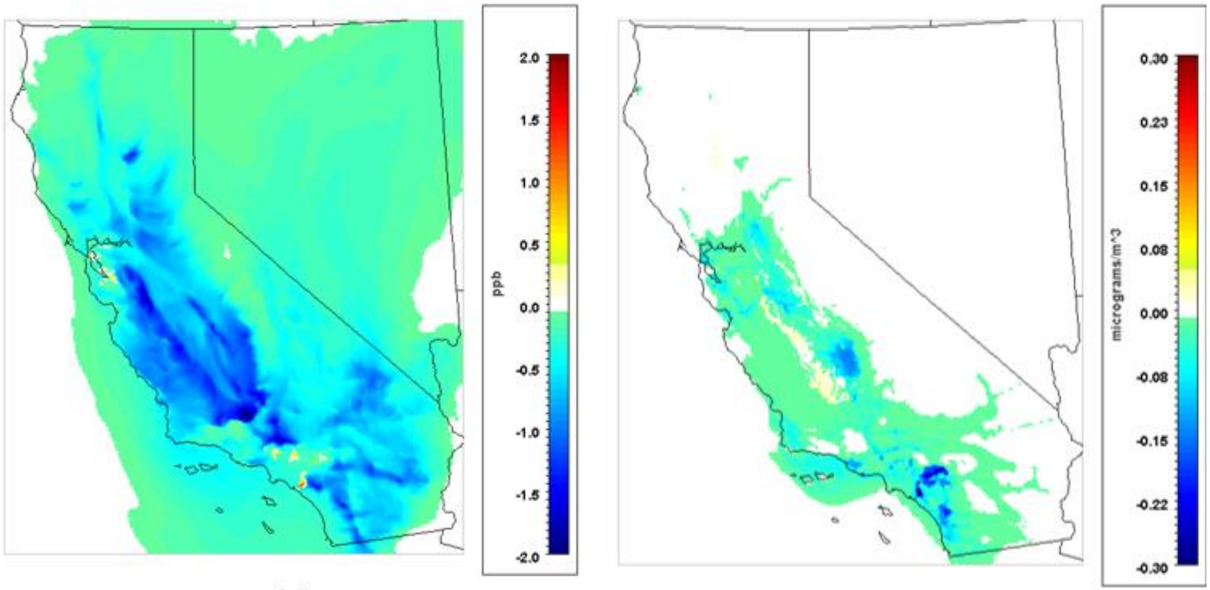
[6] https://www.arb.ca.gov/planning/sip/sjvpm25/workshopslides.pdf



(a) (b)

Figure 19. Ambient 24-hr average $PM_{2.5}$ for the Base Case for (a) Summer and (b) Winter

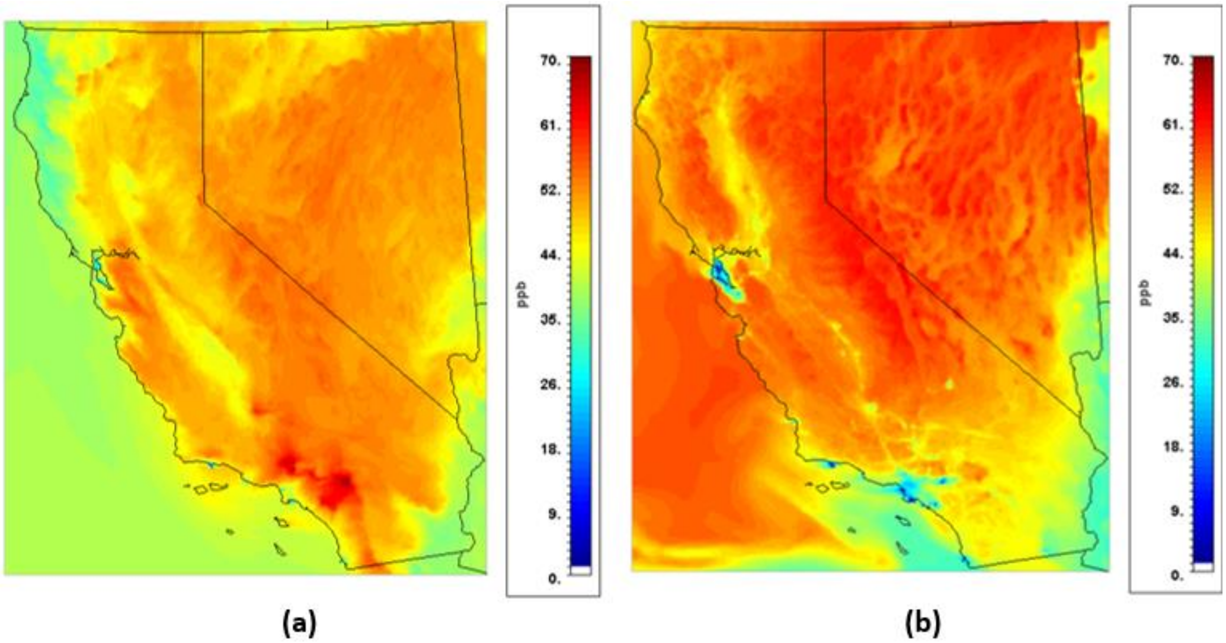
Case 1B



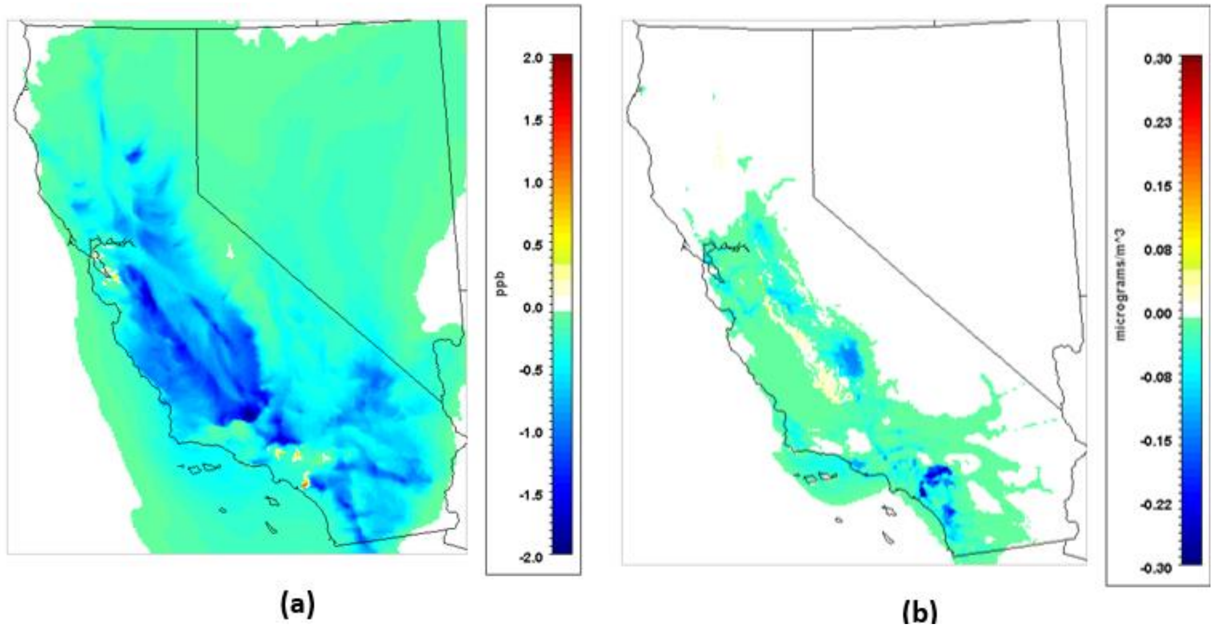
(a) (b)

Figure 20 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the Base and 1B Case for the summer episode. Reductions in ozone reach -5.09 ppb and -2.77 ppb in maximum 1-hr and 8-hr average, respectively. Areas of highest impact occur

downwind of roadways in areas of the state associated with high levels of ozone (shown in Figure 18) including the SoCAB, Central Valley, S.F. Bay Area and Sacramento. Reductions in $PM_{2.5}$ reach -1.28 ug/m^3 and -0.60 ug/m^3 in maximum 1-hr and 24-hr average, respectively. Improvements are most notable in SoCAB, and important reductions also occur in the Central Valley and east of the S.F. Bay Area.



(a) (b)



(a) (b)

Figure 20. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 1B relative to the Base Case

Figure 21 displays the predicted difference in 24-hr $PM_{2.5}$ between the Base and 1B Case for the winter episode. Improvements in ground-level $PM_{2.5}$ are significant with reductions reaching -6.26 ug/m^3 and -3.41 ug/m^3 in maximum 1-hr and 24-hr average, respectively. Improvements are notable throughout the State with the S.F. Bay Area and Central Valley associated with peak reductions. Relatively, small impacts are observed in southern California.

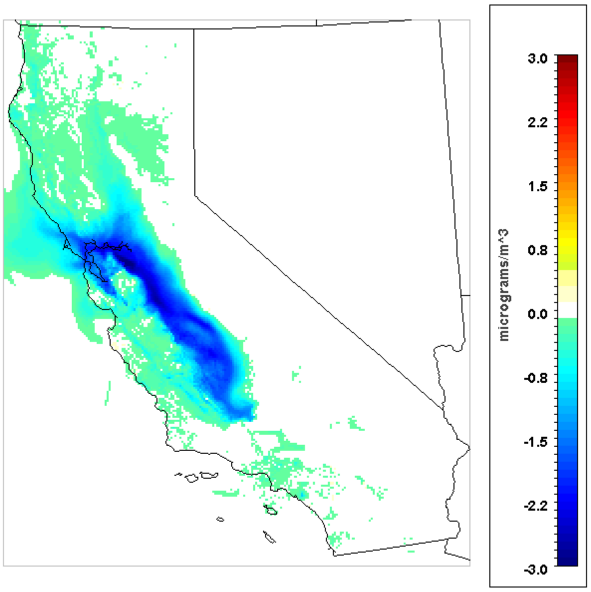
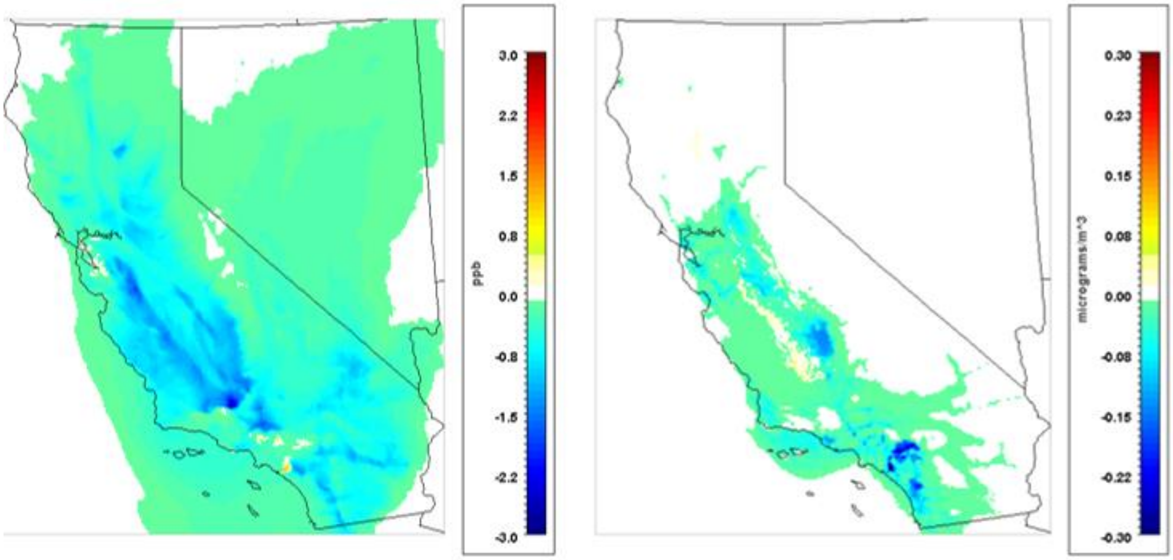


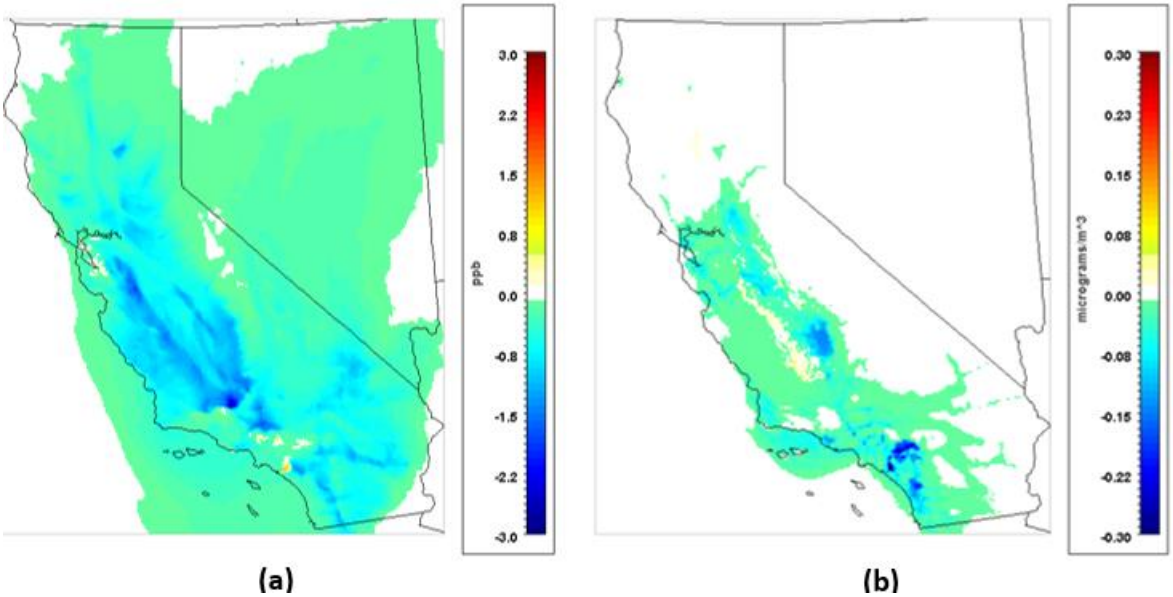
Figure 21. Predicted difference in winter episode 24-hr average $PM_{2.5}$ for Case 1B relative to the Base Case

Case 2B



(a) **(b)**

Figure 22 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the Base and 2B Case for the summer episode. Reductions in ozone reach -5.04 ppb and -2.73 ppb in maximum 1-hr and 8-hr average, respectively. Areas of highest impact are the same as those in Case 1B and occur in the SoCAB, Central Valley, S.F. Bay Area and Sacramento. Reductions in $PM_{2.5}$ reach -1.24 ug/m^3 and -0.59 ug/m^3 in maximum 1-hr and 24-hr average, respectively. Similar to ozone, the spatial area of impact is equivalent to those in Case 1B. Ozone and $PM_{2.5}$ impacts are slightly reduced from Case 1B, as would be expected when considering emission trends.



(a) (b)

Figure 22. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 2B relative to the Base Case

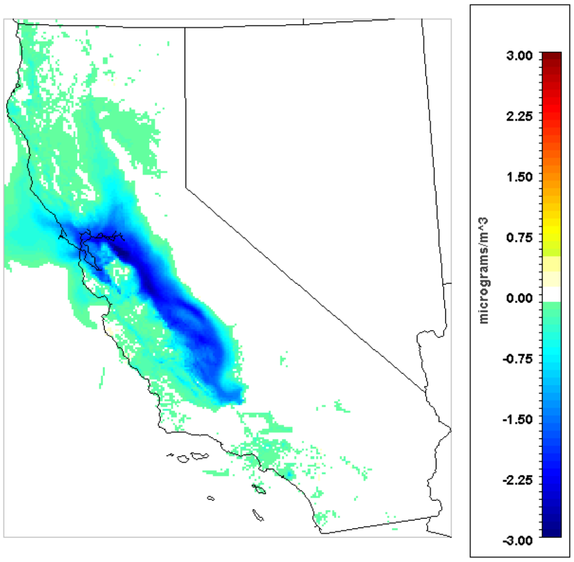


Figure 23 displays the predicted difference in 24-hr $PM_{2.5}$ between the Base and 2B Case for the winter episode. Improvements in ground-level $PM_{2.5}$ are significant with reductions reaching -6.26 ug/m^3 and -3.36 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

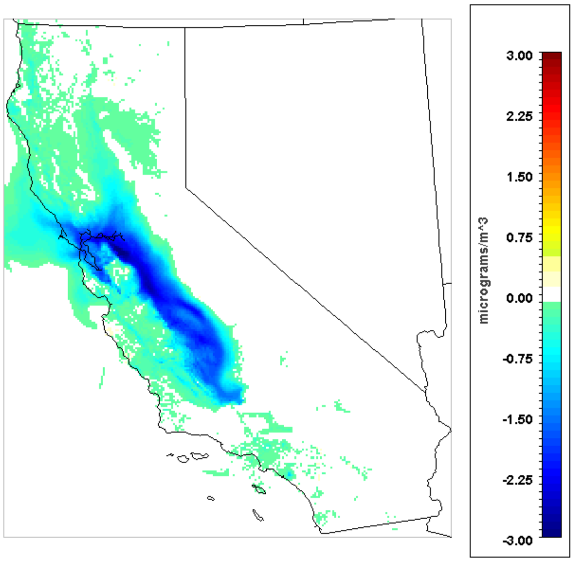
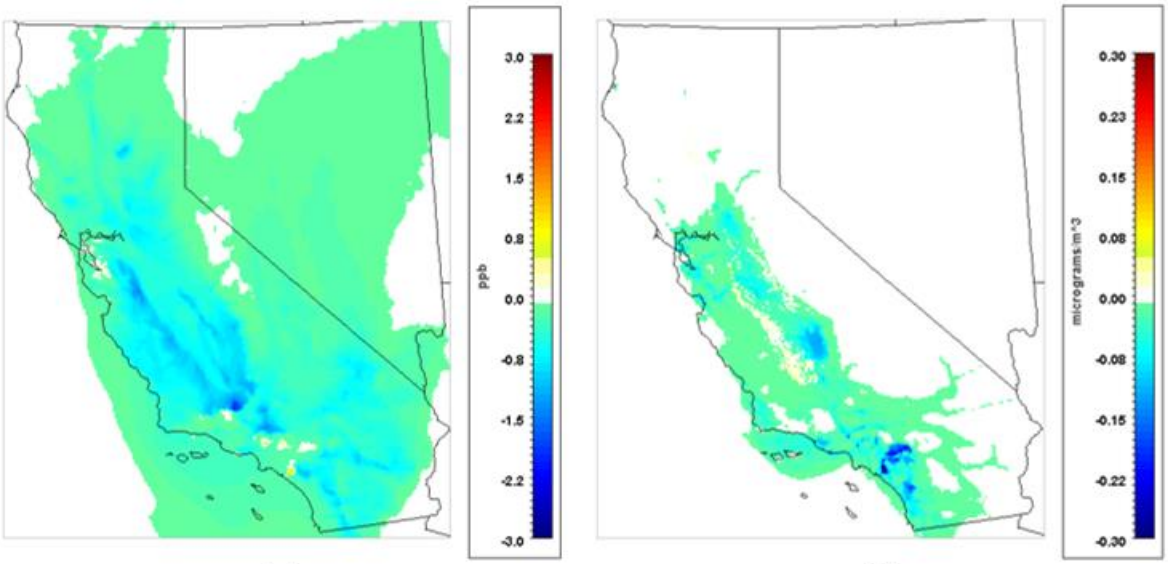


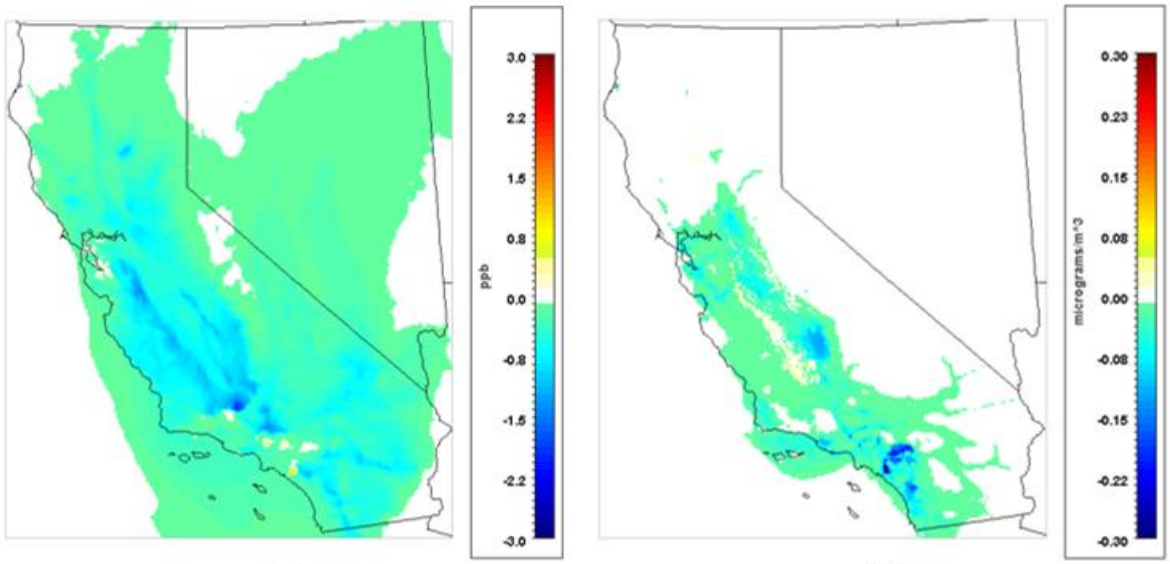
Figure 23. Predicted difference in winter episode 24-hr average $PM_{2.5}$ for Case 2B relative to the Base Case

Case 3B



(a) (b)

Figure 24 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the Base and 3B Cases for the summer episode. Reductions in ozone reach -3.91 ppb and -2.14 ppb in maximum 1-hr and 8-hr average, respectively. Reductions in $PM_{2.5}$ reach -1.20 ug/m^3 and -0.54 ug/m^3 in maximum 1-hr and 24-hr average, respectively.



(a)

(b)

Figure 24. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 3B relative to the Base Case

Figure 25 displays the predicted difference in 24-hr $PM_{2.5}$ between the Base and 3B Case for the winter episode. Improvements in ground-level $PM_{2.5}$ reaching -5.97 ug/m^3 and -2.71 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

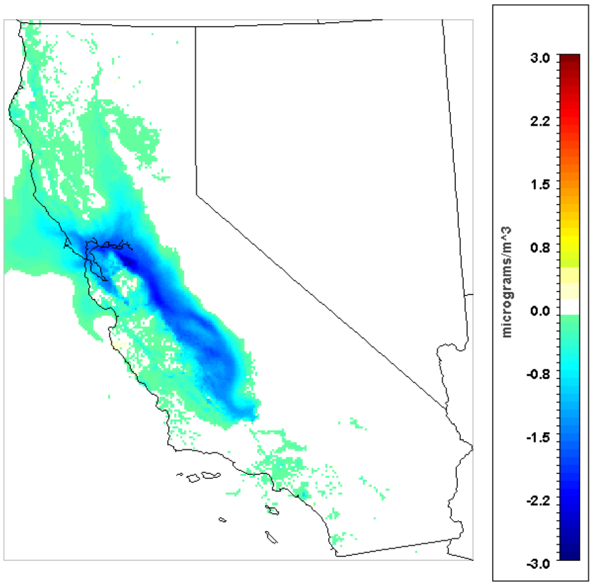
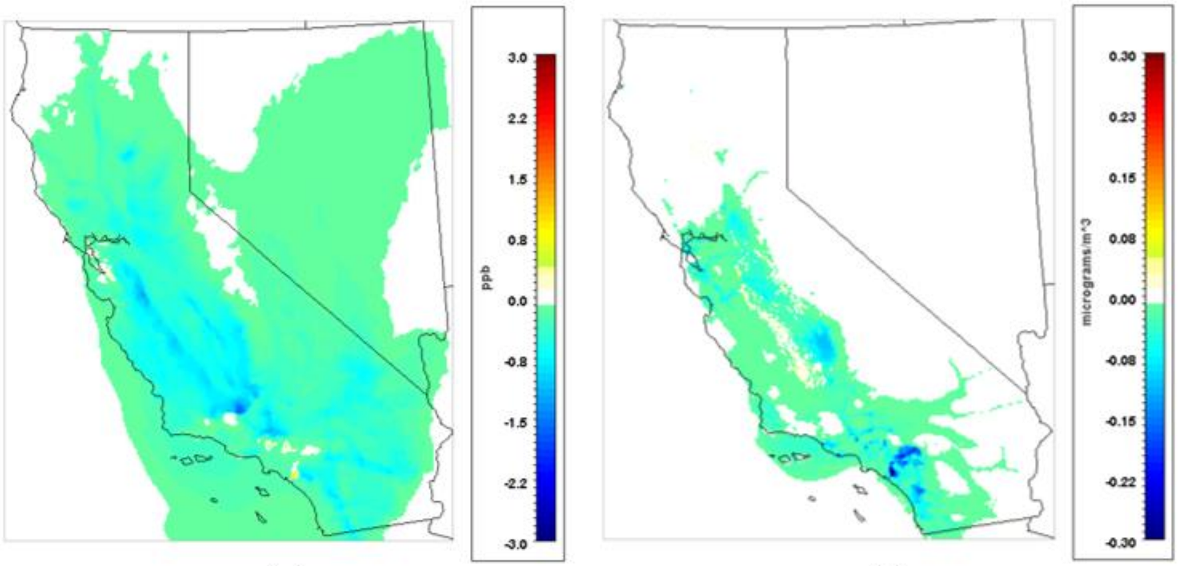


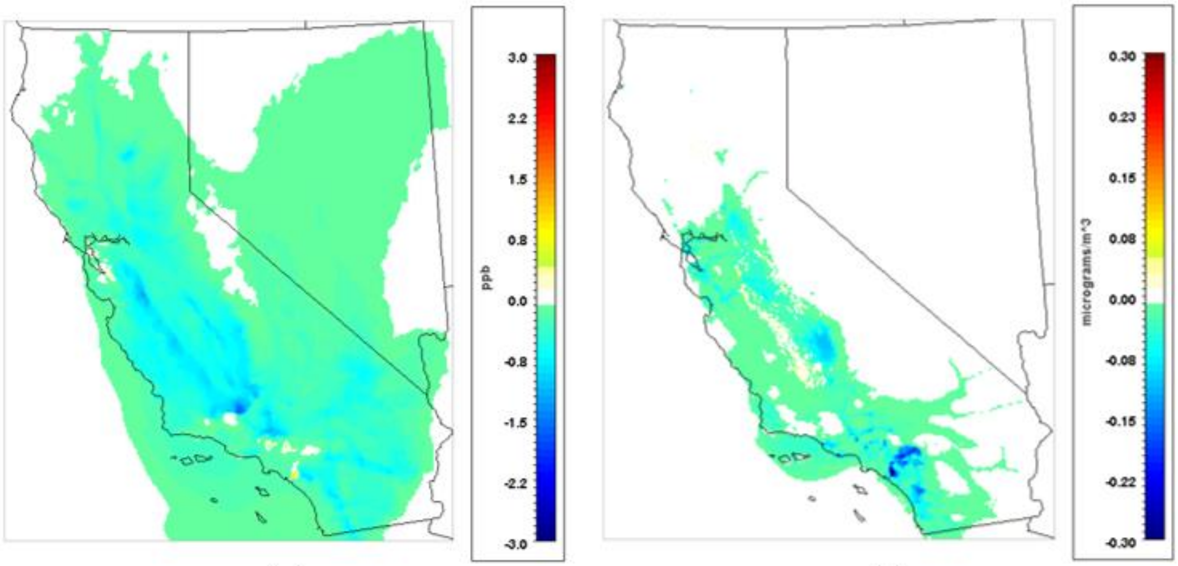
Figure 25. Predicted difference in winter episode 24-hr average $PM_{2.5}$ for Case 3B relative to the Base Case

Case 4B



(a) **(b)**

Figure 26 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the Base and 4B Cases for the summer episode. Reductions in ozone reach -3.33 ppb and -0.97 ppb in maximum 1-hr and 8-hr average, respectively. Ozone impacts are the lowest for all considered scenarios as it represents the case with minimal NO_x emission reductions. Reductions in $PM_{2.5}$ reach -1.17 ug/m^3 and -0.52 ug/m^3 in maximum 1-hr and 24-hr average, respectively.



(a) **(b)**

Figure 26. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 4B relative to the Base Case

Figure 27 displays the predicted difference in 24-hr $PM_{2.5}$ between the Base and 4B Case for the winter episode. Improvements in ground-level $PM_{2.5}$ reaching -5.91 ug/m^3 and -2.34 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

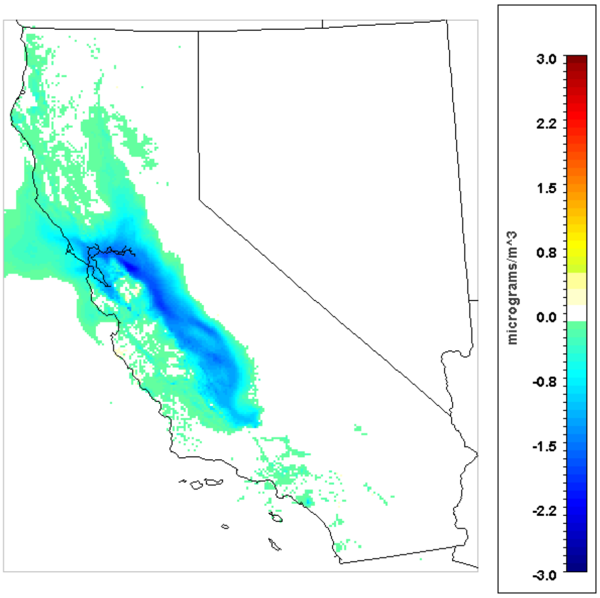


Figure 27. Predicted difference in winter episode 24-hr average $PM_{2.5}$ for Case 4B relative to the Base Case

Base Case Conclusions

Comparison of the cases with the Base Case provides insight into the AQ impacts of advanced CNG vehicles as the predominant alternative technology relative to a future where vehicle technology remains relatively constant to current with little deployment of additional clean technologies, i.e., the baseline HDV and MDV sector is associated with the highest emissions. Therefore the results provide an upper bound for the AQ benefits of advanced CNG as it is likely that the 2035 vehicle fleet will be comprised of a mix of cleaner technologies.

Table 13 displays the differences in peak ozone and $PM_{2.5}$ concentrations from the Base Case predicted in the summer episode. Impacts on ozone correspond to the NO_x emission reduction trends with the largest predicted difference from Case 1B (All HDV and MDV advanced CNG) and the lowest from Case 4B. Quantitatively, ozone impacts range from -2.77 to -0.97 ppb max 8-hr in peak value. This is particularly notable given that the modeled episode does not produce exceptionally high baseline levels and is likely that for an extreme episode the achieved reduction may be even more significant. Spatially, impacts occur downwind of locations of vehicle activity including along the major transportation corridors in the Central Valley. Similarly, areas downwind of urban areas supporting large numbers of vehicles include the SoCAB and S.F. Bay Area. These locations are of importance because (1) these areas are associated with high baseline levels and (2) they support large populations with implications for human health benefits. Across cases, the spatial locations of impact are the same for both ozone and $PM_{2.5}$, which is expected given the equivalent assumption of spatial source apportionment remaining constant.

Summer and winter $PM_{2.5}$ (Table 13 and Table 14) impacts follow similar trends quantitatively with Case 1B achieving the highest benefits and Case 4A achieving the lowest reductions in concentrations. However, between cases impacts are relatively small, ranging from -0.6 ug/m^3 to -0.52 ug/m^3 in summer and -3.63 ug/m^3 to -2.71 ug/m^3 winter. In the summer episode peak impacts occur in the SoCAB, with notable impacts also occurring in the Central Valley. Impacts are particularly large for the Central Valley in winter indicative of both the high baseline levels within the Central Valley during winter and the moderate levels modeled in the summer episode.

It should be noted that while valuable conclusions can be made from quantification of peak impacts, assessment should not be based solely on that as a metric. This is because a description of the peak impacts refers to the single largest predicted difference for one cell within the modeling grid, i.e., within one 4 km by 4 km area. Thus, other criteria that are important for understanding AQ impacts should also be taken into account including the area of impact, the importance of considering initial baseline levels, etc.

Table 13. Δ Peak ozone and $PM_{2.5}$ concentrations predicted for Summer from the Base Case

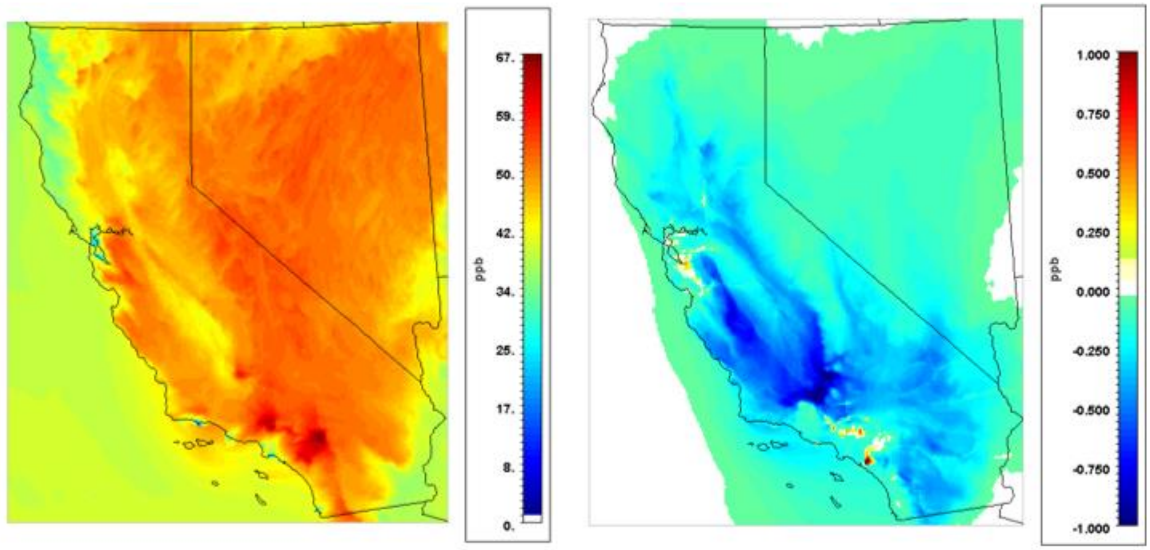
	Ground-level Ozone		Ground-level $PM_{2.5}$	
Case	**Max 1-hr**	**Max 8-hr**	**Max 1-hr**	**Max 24-hr**
1B	-5.09 ppb	-2.77 ppb	-1.28 ug/m^3	-0.60 ug/m^3
2B	-5.04 ppb	-2.73 ppb	-1.24 ug/m^3	-0.59 ug/m^3
3B	-3.91 ppb	-2.14 ppb	-1.20 ug/m^3	-0.54 ug/m^3
4B	-3.33 ppb	-0.97 ppb	-1.17 ug/m^3	-0.52 ug/m^3

Table 14. Δ Peak $PM_{2.5}$ concentrations predicted for Winter from the Base Case

	Ground-level $PM_{2.5}$	
Case	**Max 1-hr**	**Max 24-hr**
1B	-6.26 ug/m^3	-3.41 ug/m^3
2B	-6.26 ug/m^3	-3.36 ug/m^3
3B	-5.97 ug/m^3	-2.71 ug/m^3
4B	-5.91 ug/m^3	-2.71 ug/m^3

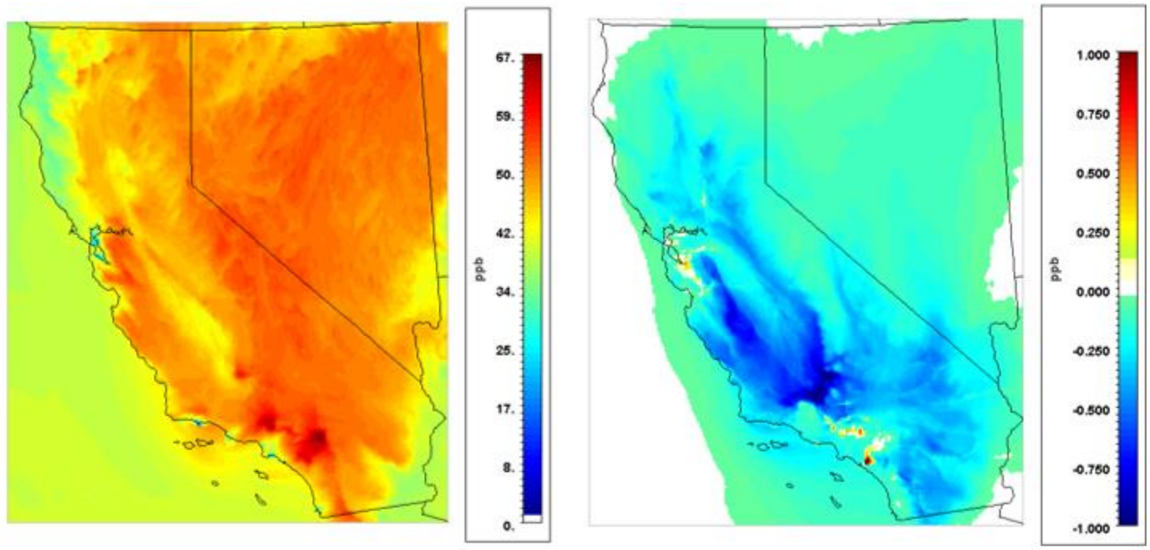
SIP Case

In the SIP Case, simulated ground-level concentrations of summer ozone reach 78 ppb and 67 ppb in maximum 1-hr and 8-hr average (shown in



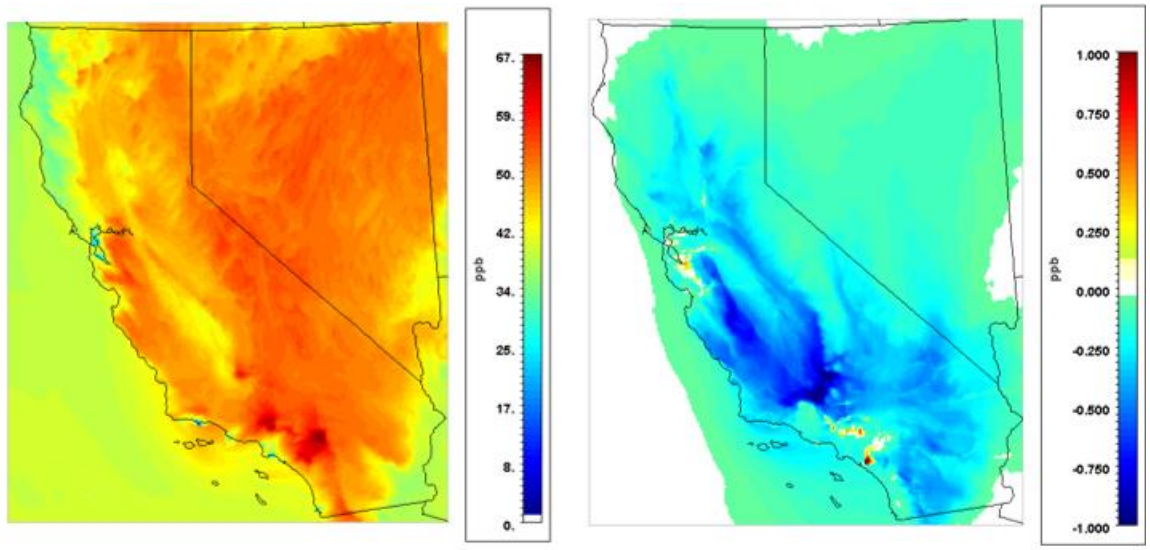
(a) (b)

Figure 28a). Peak levels are comparable spatially to those predicted for the Base Case.



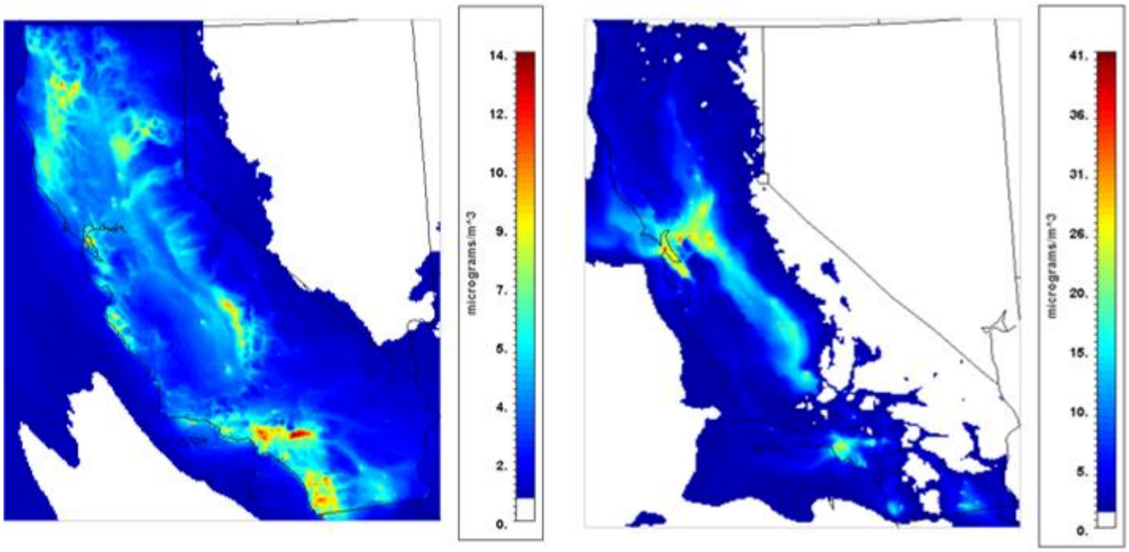
(a) **(b)**

Figure 28b shows a difference plot in 8-hr ozone between the SIP Case and Base Case. Reductions in ozone attributable to reductions in NO_x of 85 tpd from the cleaner mix of HDV and MDV in the SIP Case and reach approximately 1.24 ppb. Therefore, the following section presents results derived from cases that assume higher deployment of advanced CNG engines relative to the SIP Case, i.e., in addition to those already achieved by the technology assumptions inherent in the SIP Case. This prevents double counting of emission reductions and yields insight into the ability of advanced CNG technologies to provide additional AQ improvements, even with a cleaner assumed technology mix as the baseline.



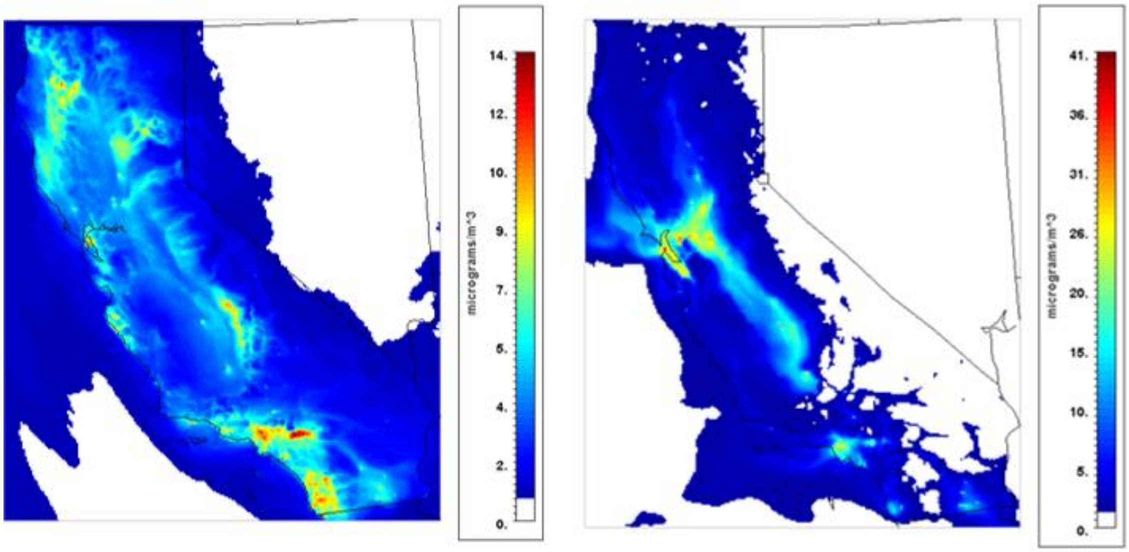
(a) **(b)**

Figure 28. (a) Ambient max 8-hr average ozone in the SIP Case for Summer and (b) the difference in maximum 8-hr ozone between the SIP and Base Case



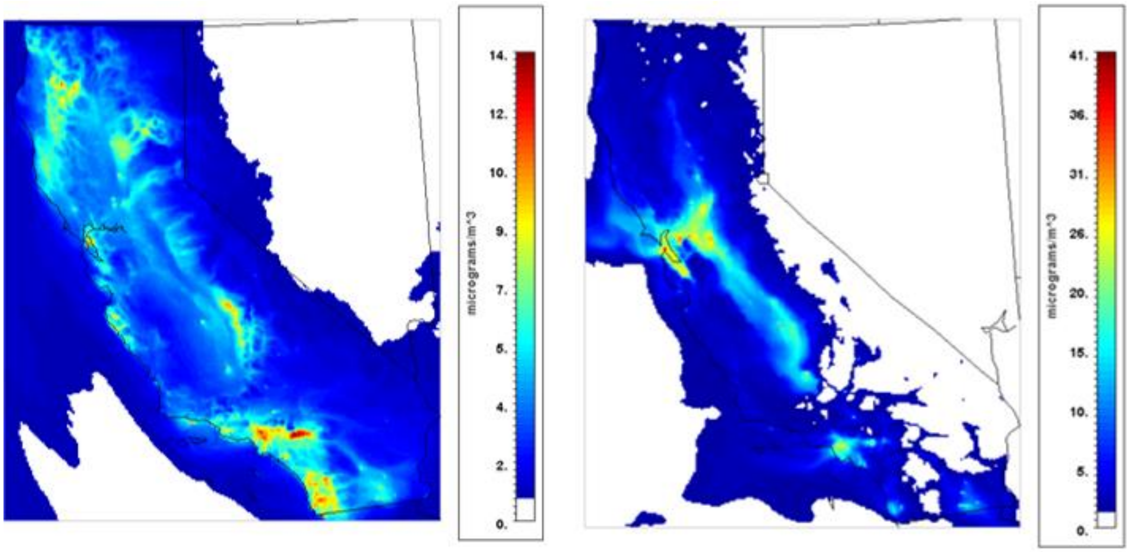
(a) (b)

Figure 29 shows the predicted 24-hr average $PM_{2.5}$ for the summer (



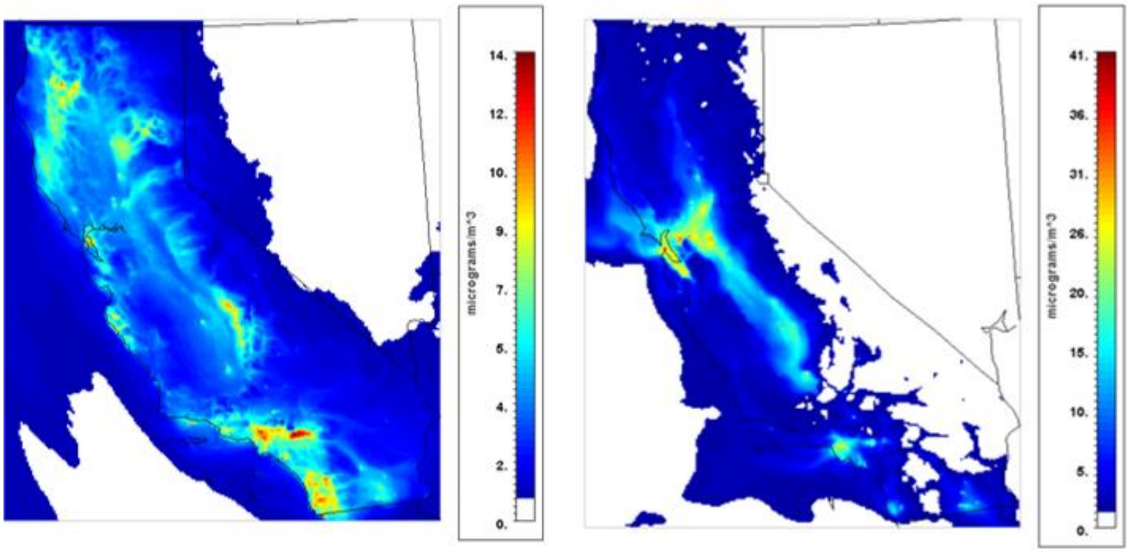
(a) (b)

Figure 29a) and winter (



(a) (b)

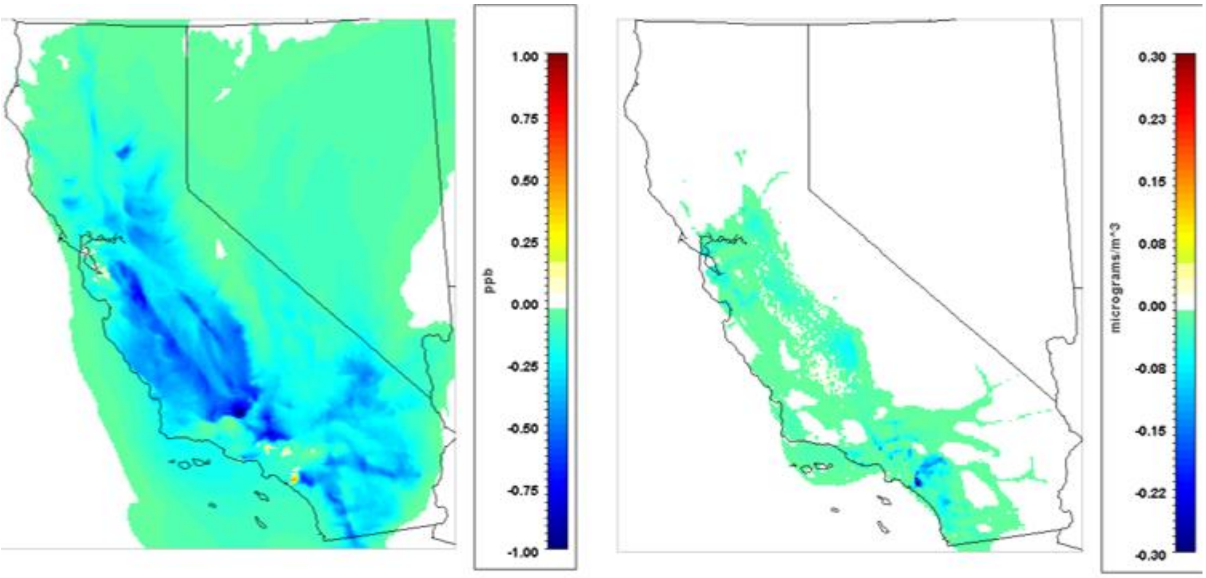
Figure 29b) cases in 2035. For the summer episode, concentrations reach 14.47 ug/m^3 with peak impacts located in areas of the SoCAB. Additional areas experiencing high levels mirror the Base Case, i.e., San Diego County, parts of the Central Valley, the Sacramento Valley, and the S.F. Bay Area. Similarly to the Base Case, PM$_{2.5}$ concentrations are higher in the winter episode, reaching 41.69 ug/m^3, and are highest in the S.F. Bay Area, Central Valley, and SoCAB. With similarity to the ozone results for the SIP Case, concentrations of PM$_{2.5}$ are lower than those for the Base Case due to the assumed cleaner technology mix.



(a) (b)

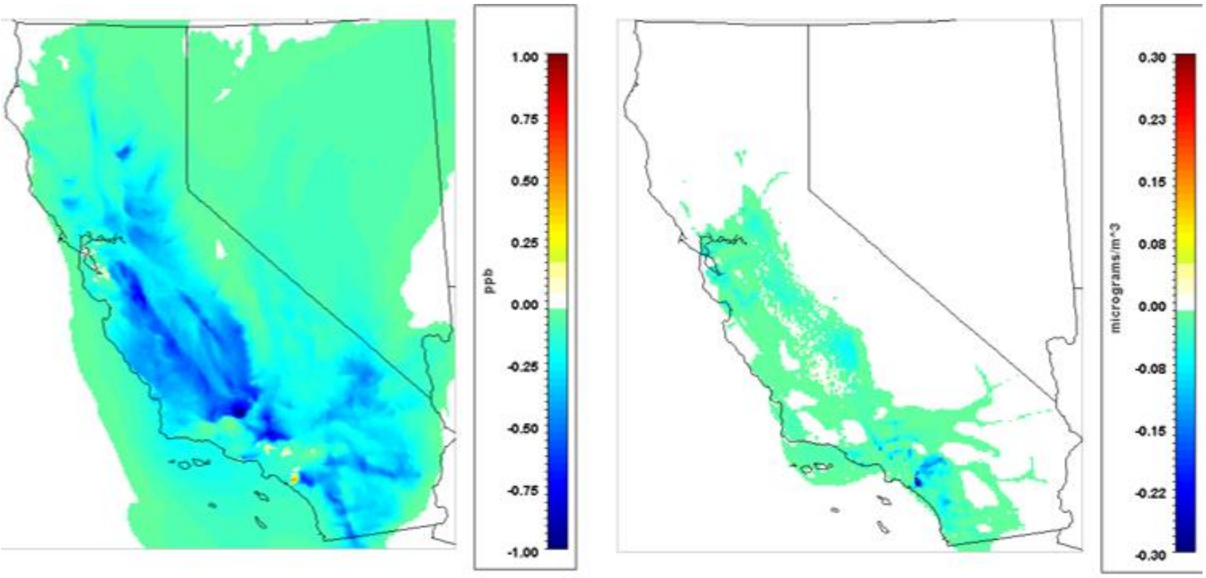
Figure 29. Ambient 24-hr PM$_{2.5}$ in the SIP Case for (a) Summer and (b) Winter in the SIP Case

Case 2A



(a) (b)

Figure 30 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the SIP and 2A Case for the summer episode. Reductions in ozone reach -2.32 ppb and -1.25 ppb in maximum 1-hr and 8-hr average, respectively. Areas of highest impact are the same as those in Case 1B and occur in the SoCAB, Central Valley, S.F. Bay Area and Sacramento. Ozone impacts are slightly reduced from Case 1B, as would be expected when considering NO_x emission trends. Reductions in $PM_{2.5}$ reach -1.14 ug/m^3 and -0.51 ug/m^3 in maximum 1-hr and 24-hr average, respectively. Of interest, $PM_{2.5}$ reductions reach a slightly higher magnitude than Case 1B.



(a) (b)

Figure 30. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average PM$_{2.5}$ for Case 2A relative to the SIP Case

Figure 31 displays the predicted difference in 24-hr PM$_{2.5}$ between the SIP and 2A Case for the winter episode. Improvements in ground-level PM$_{2.5}$ are significant with reductions reaching -5.87 ug/m^3 and -1.50 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

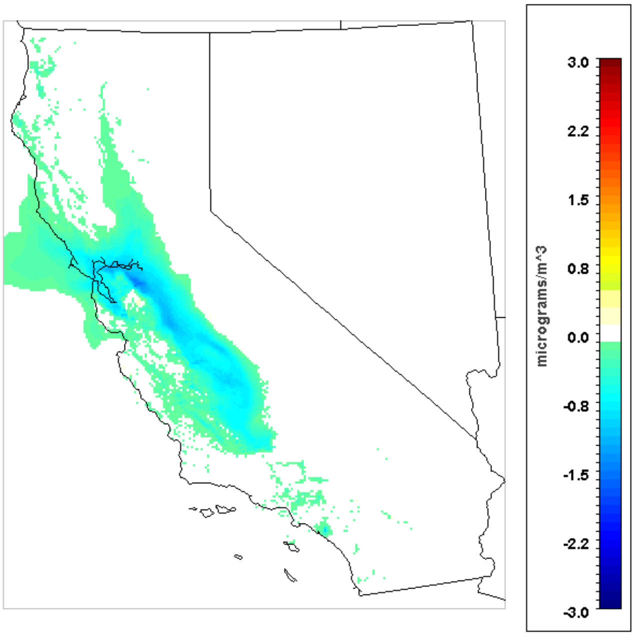
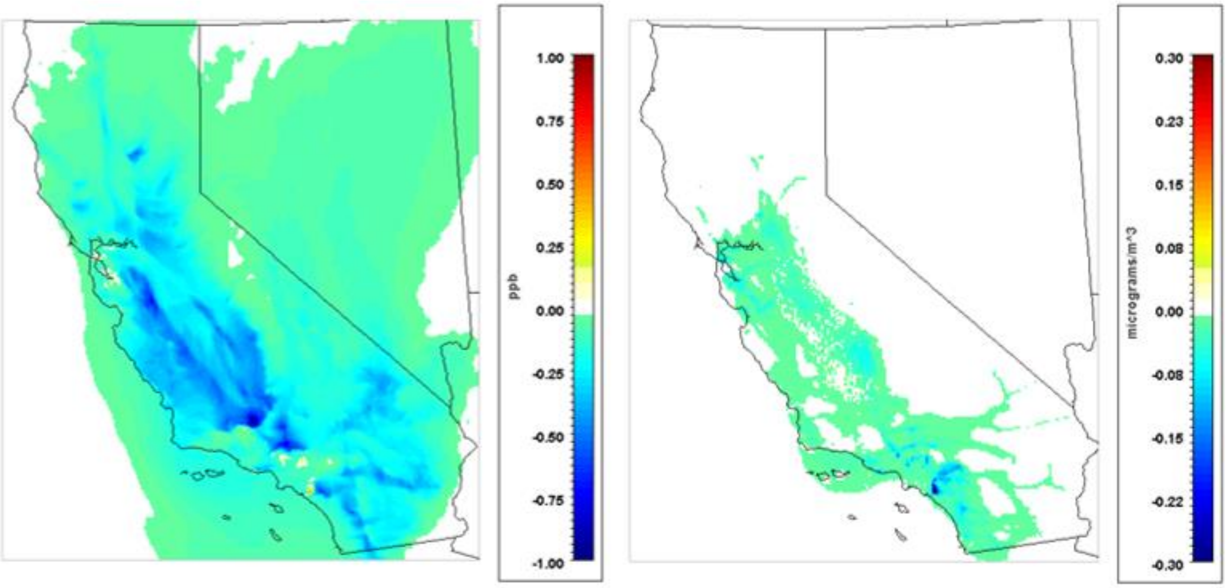


Figure 31. Predicted difference in winter episode 24-hr average PM$_{2.5}$ for Case 2A relative to the SIP Case

Case 2C

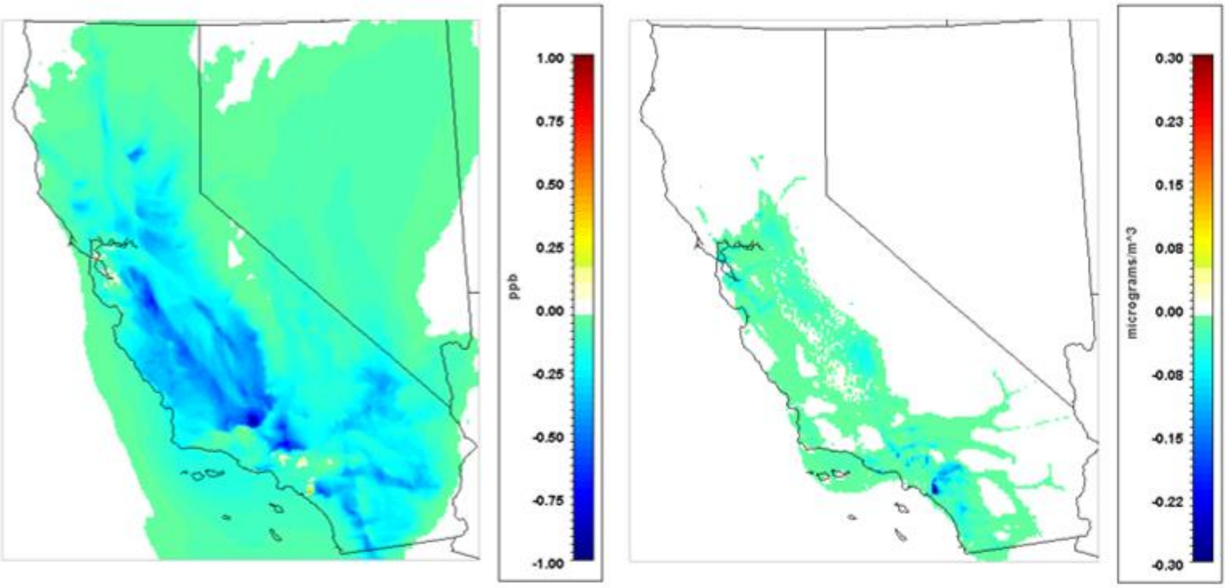
The assumptions in Case 2D (All likely categories of HDV in Table 5) result in approximately 41% of HDV transitioning to advanced CNG engines and 50% of MDV.



(a)

(b)

Figure 32 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the SIP and 2C Cases for the summer episode. Reductions in ozone reach -1.99 ppb and -1.08 ppb in maximum 1-hr and 8-hr average, respectively. Reductions in $PM_{2.5}$ reach -1.12 ug/m^3 and -0.50 ug/m^3 in maximum 1-hr and 24-hr average, respectively.



(a)

(b)

Figure 32. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 2C relative to the SIP Case

Figure 33 displays the predicted difference in 24-hr $PM_{2.5}$ between the SIP and 2C Case for the winter episode. Improvements in ground-level $PM_{2.5}$ reaching -5.75 ug/m^3 and -1.31 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

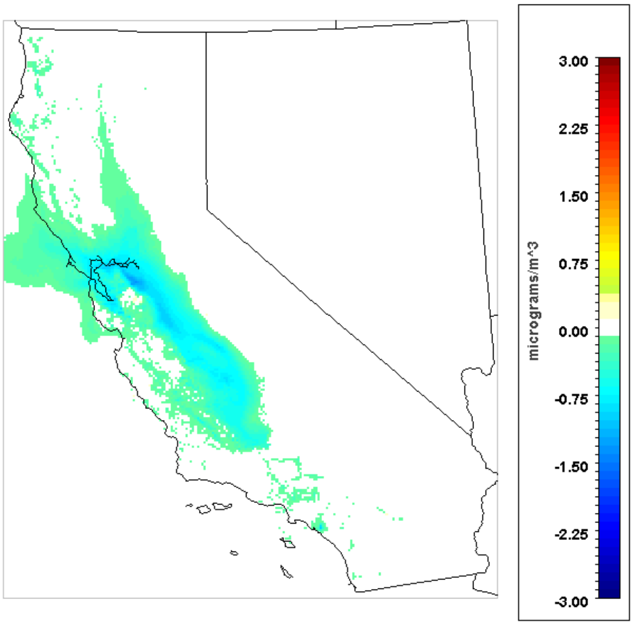
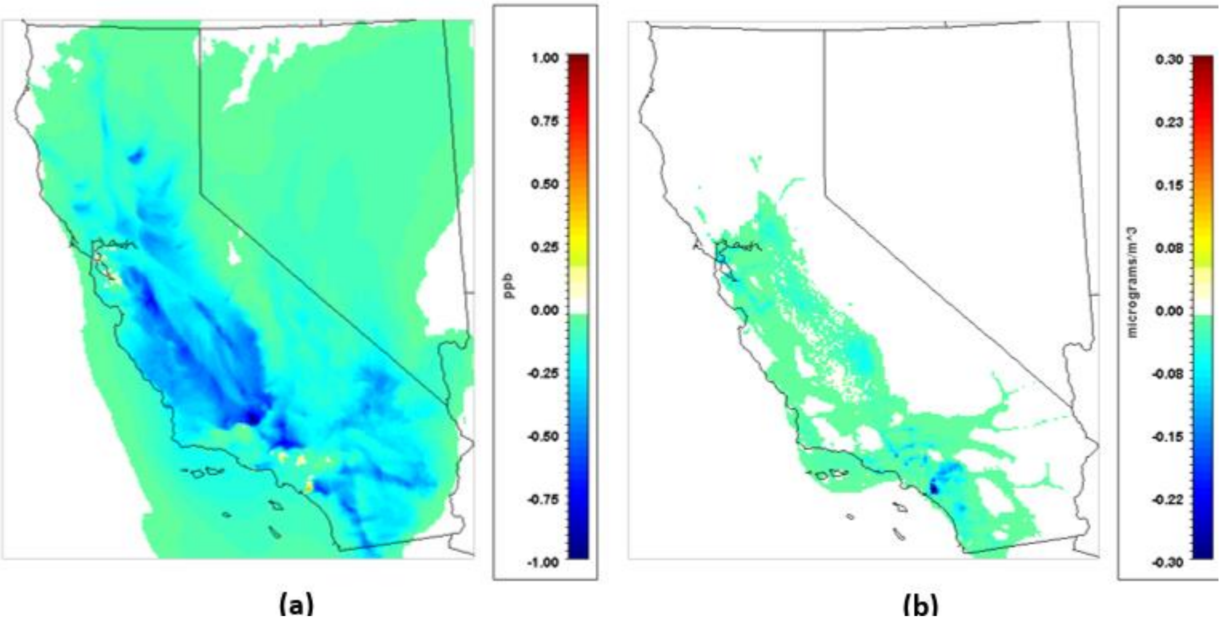


Figure 33. Predicted difference in winter episode 24-hr average $PM_{2.5}$ for Case 2C relative to the SIP Case

Case 2D

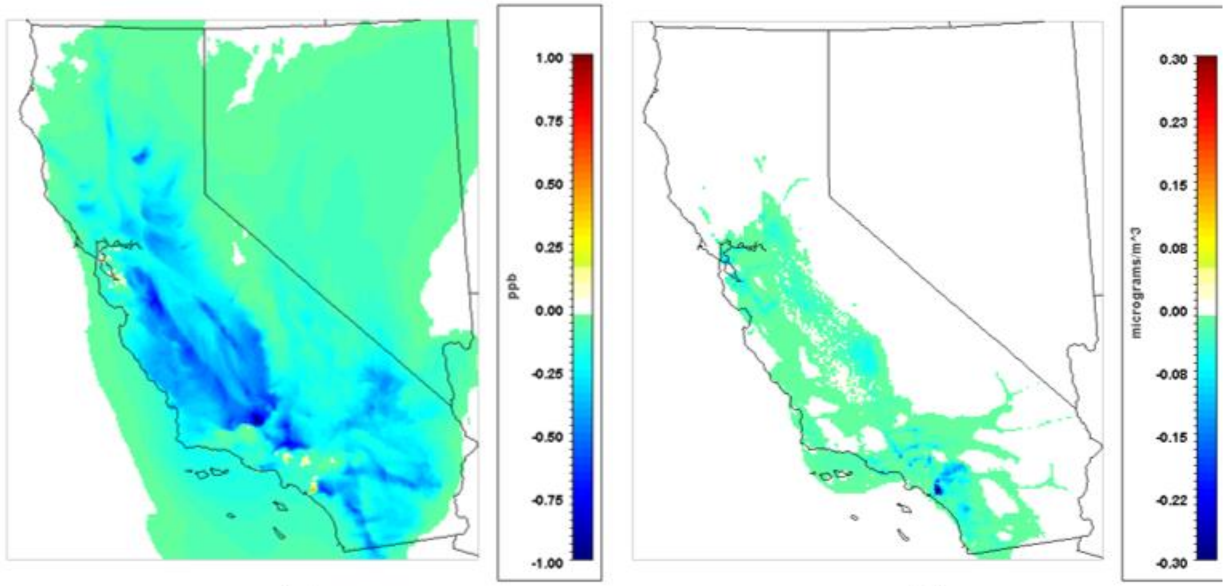
The assumptions in Case 2D (100% of in-state vehicles) result in approximately 60% of HDV transitioning to advanced CNG engines and 50% of MDV.



(a)

(b)

Figure 34 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the SIP and 2D Cases for the summer episode. Reductions in ozone reach -2.18 ppb and -1.18 ppb in maximum 1-hr and 8-hr average, respectively. Reductions in $PM_{2.5}$ reach -1.13 ug/m^3 and -0.50 ug/m^3 in maximum 1-hr and 24-hr average, respectively.



(a) (b)

Figure 34. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 2D relative to the SIP Case

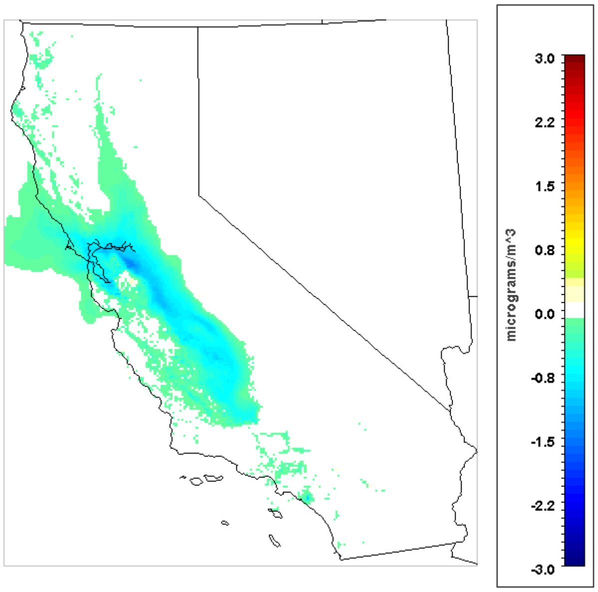


Figure 35 displays the predicted difference in 24-hr $PM_{2.5}$ between the SIP and 2D Case for the winter episode. Improvements in ground-level $PM_{2.5}$ reaching -5.75 ug/m^3 and -1.43 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

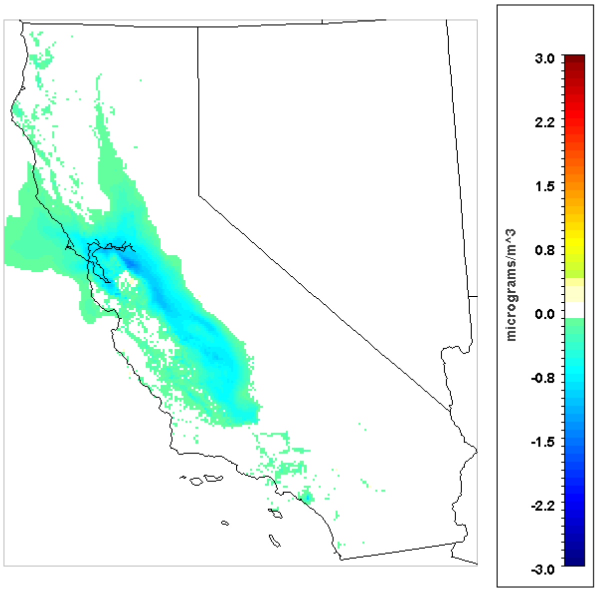
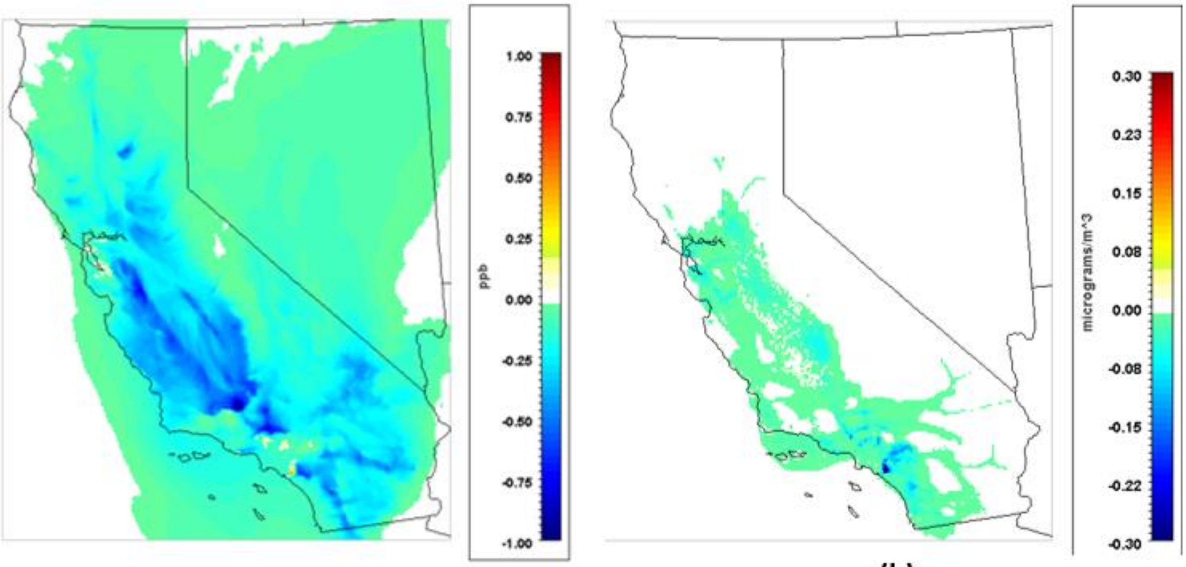


Figure 35. Predicted difference in winter episode 24-hr average PM$_{2.5}$ for Case 2D relative to the SIP Case

Case 3A



(a) **(b)**

Figure 36 displays the predicted difference in maximum 8-hour ozone and 24-hour PM$_{2.5}$ between the SIP and 3A Cases for the summer episode. Reductions in ozone reach -2.17 ppb and -1.17 ppb in maximum 1-hr and 8-hr average, respectively. Reductions in PM$_{2.5}$ reach -1.13 ug/m^3 and -0.50 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

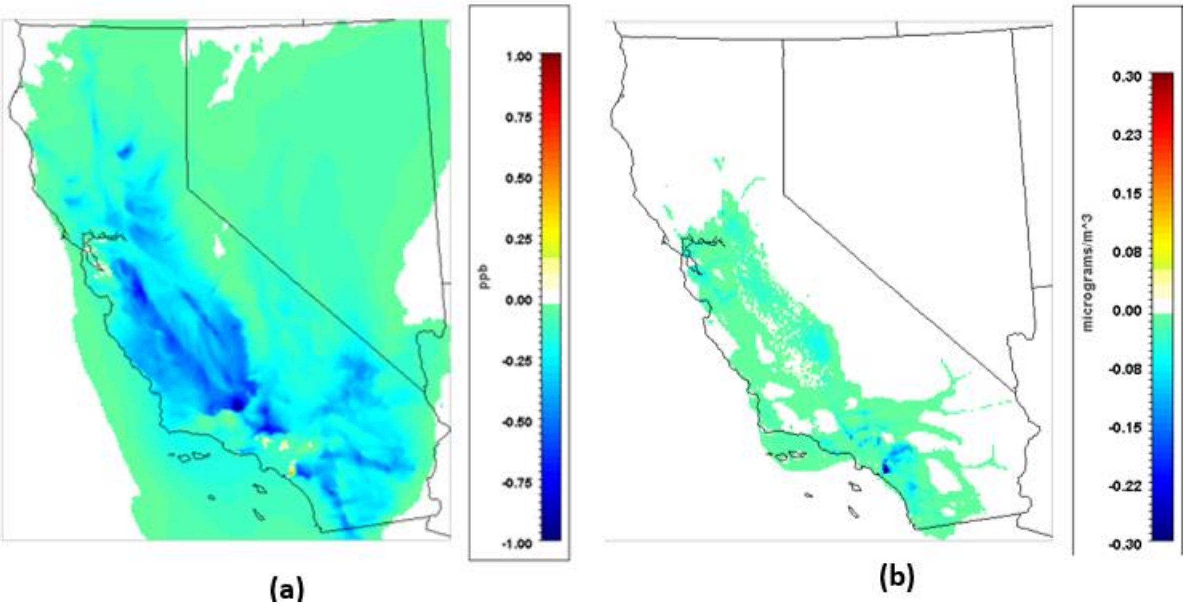


Figure 36. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 3A relative to the SIP Case

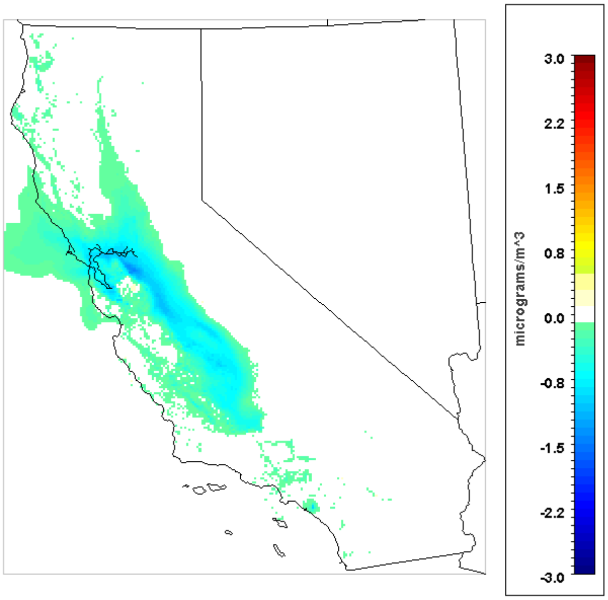


Figure 37 displays the predicted difference in 24-hr $PM_{2.5}$ between the SIP and 3A Case for the winter episode. Improvements in ground-level $PM_{2.5}$ reaching -5.75 ug/m^3 and -1.42 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

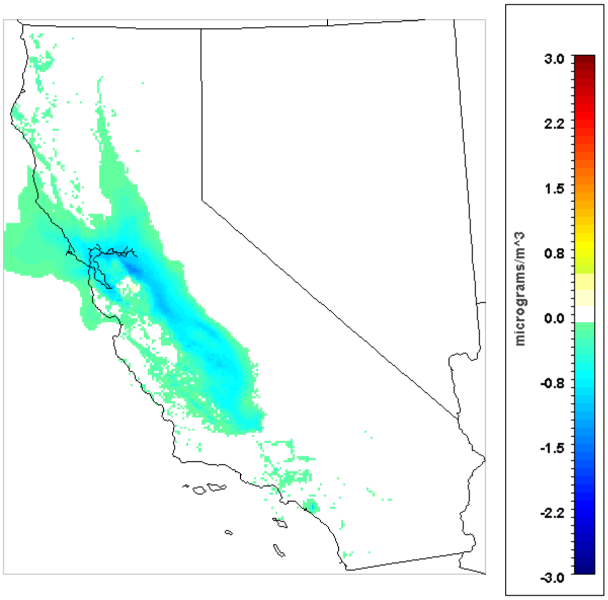
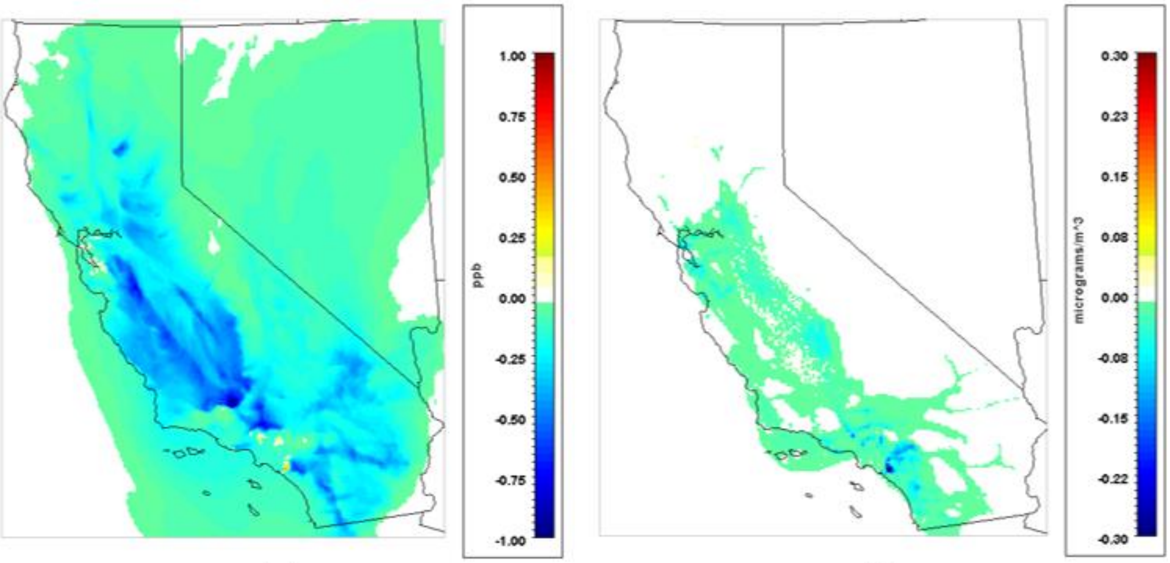


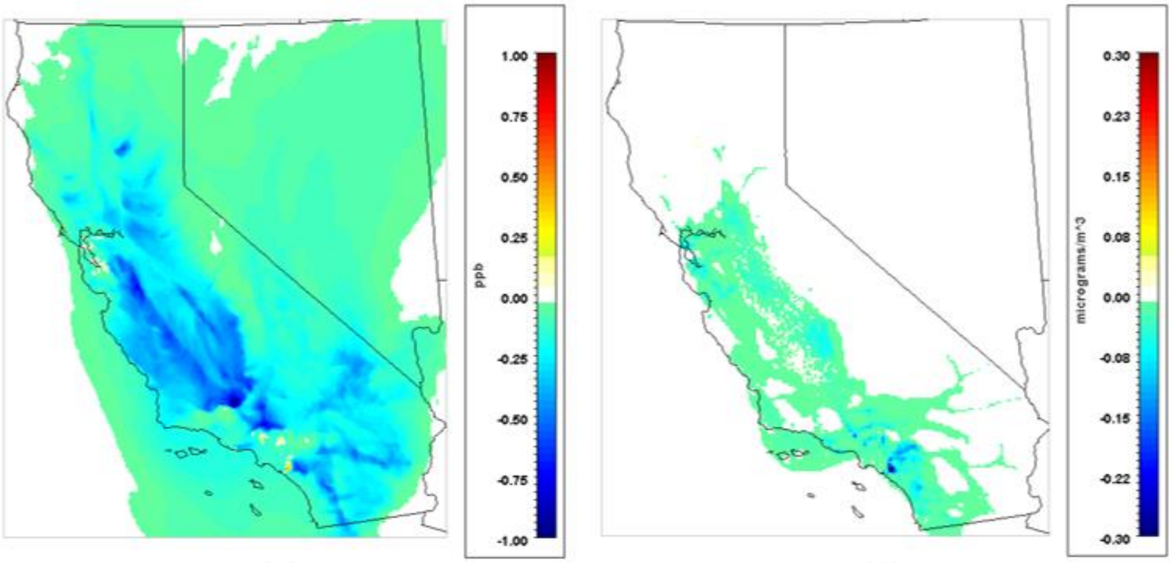
Figure 37. Predicted difference in winter episode 24-hr average $PM_{2.5}$ for Case 3A relative to the SIP Case

Case 4A



(a) **(b)**

Figure 38 displays the predicted difference in maximum 8-hour ozone and 24-hour $PM_{2.5}$ between the SIP and 4A Cases for the summer episode. Reductions in ozone reach -2.15 ppb and -1.16 ppb in maximum 1-hr and 8-hr average, respectively. Reductions in $PM_{2.5}$ reach -1.13 ug/m^3 and -0.50 ug/m^3 in maximum 1-hr and 24-hr average, respectively.



(a) (b)

Figure 38. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 4A relative to the SIP Case

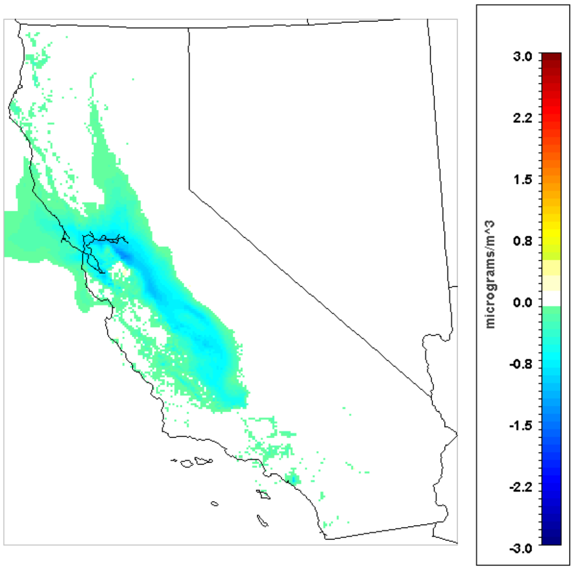


Figure 39 displays the predicted difference in 24-hr $PM_{2.5}$ between the SIP and 4A Case for the winter episode. Improvements in ground-level $PM_{2.5}$ reaching -5.75 ug/m^3 and -1.41 ug/m^3 in maximum 1-hr and 24-hr average, respectively.

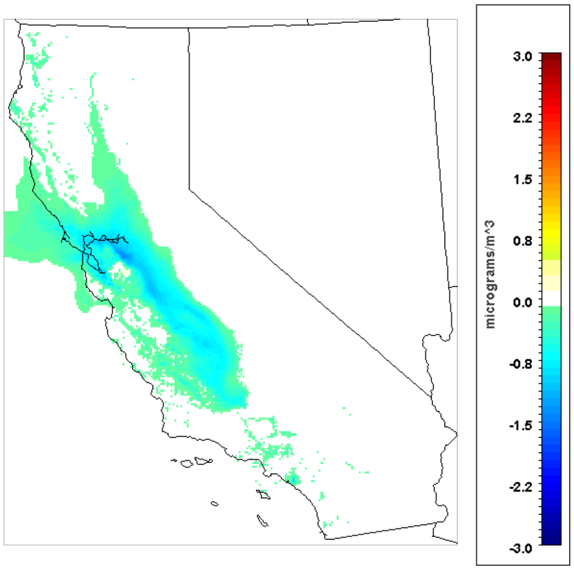


Figure 39. Predicted difference in winter episode 24-hr average $PM_{2.5}$ for Case 4A relative to the SIP Case

SIP Case Conclusions

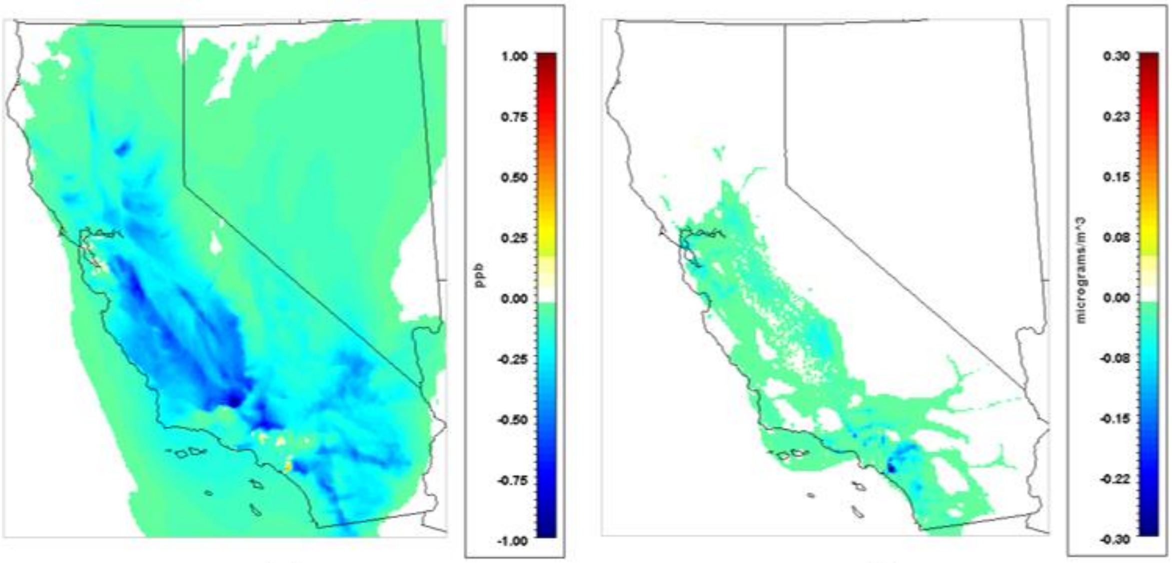
Comparison of the following cases with the SIP Case provides insight into how increasing the penetration of advanced CNG engines can further achieve AQ improvements within the context of a cleaner portfolio of HDV and MDV technologies. Table 15 displays the peak ozone and $PM_{2.5}$ concentrations predicted in summer between the SIP Case and the considered alternative Cases. As noted for the Base Case, peak reductions are not a comprehensive measure of pollutant impacts as they do not capture spatial considerations, nor do they serve as a measure of total reduction. In summer, ozone and $PM_{2.5}$ impacts follow NO_x emission reduction trends, with Case 2A (75% reduction) having the largest impact of -1.25 ppb and Case 2C (65% reduction) having the lowest impact of -1.16 ppb. Contrastingly, impacts on $PM_{2.5}$ remain relatively constant across cases with peak reductions of -0.51 ug/m^3 to -0.50 ug/m^3.

Table 15. Δ Peak ozone and $PM_{2.5}$ concentrations predicted for Summer from the SIP Case

	Ground-level Ozone		Ground-level $PM_{2.5}$	
Case	**Max 1-hr**	**Max 8-hr**	**Max 1-hr**	**Max 24-hr**
2A	-2.32 ppb	-1.25 ppb	-1.14 ug/m^3	-0.51 ug/m^3
2C	-1.99 ppb	-1.08 ppb	-1.12 ug/m^3	-0.50 ug/m^3
2D	-2.18 ppb	-1.18 ppb	-1.13 ug/m^3	-0.50 ug/m^3
3A	-2.17 ppb	-1.17 ppb	-1.13 ug/m^3	-0.50 ug/m^3

4A	-2.15 ppb	-1.16 ppb	-1.13 ug/m^3	-0.50 ug/m^3

To better characterize the range of impact spanning all of the SIP Cases,



(a) (b)

Figure 38 shows a difference plot in predicted ozone and PM$_{2.5}$ between Case 2A and Case 2C – the difference between complete deployment of advanced CNG in HDV and 50% in MDV deployment relative to applications for HDV which appear most likely at current (equating to approximately 40% of HDV) and 50% of MDV. Differences in max 8-hr average are moderate, peaking at 0.17 ppb, with maximum impacts located in the Central Valley. However, impacts are widespread throughout California and occur in many regions associated with high populations and existing AQ concerns, heightening the importance of reductions. Displaying the minor differences in predicted PM$_{2.5}$ across cases, impacts between Case 2A and Case 2C peak at .017 ug/m^3.

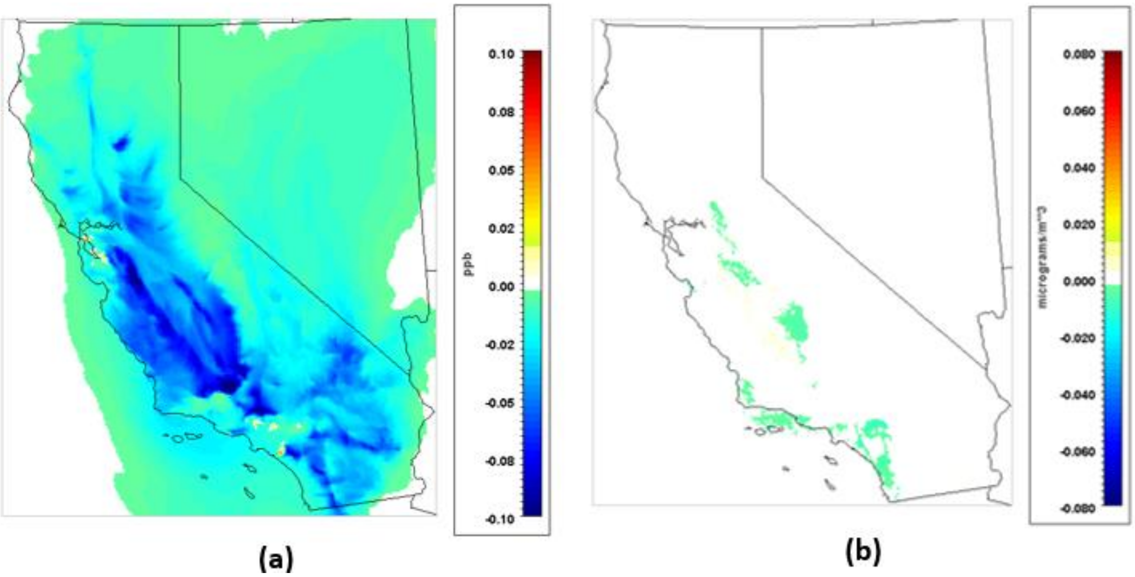


Figure 40. Predicted difference in summer episode (a) max 8-hr ozone and (b) 24-hr average $PM_{2.5}$ for Case 2A relative to Case 2C

Table 16 displays the $PM_{2.5}$ concentrations predicted in winter between the SIP Case and the considered alternative Cases. As with the Base Case, ozone impacts are quantified but not reported here due to the low background concentrations present in winter for California. Impacts on $PM_{2.5}$ are significant for all cases, with the largest reduction observed in the 2A Case of -1.50 ug/m^3 for 24-h average, and the lowest in Case 2C of -1.31 ug/m^3. In contrast to ozone impacts in summer, impacts between the cases are characterized by differences in NO_x emission reductions. This is indicative of the role of reductions in secondary $PM_{2.5}$ in ground-level concentrations as differences in emissions of $PM_{2.5}$ and ROG between the Cases are minor compared to those for NO_x.

Table 16. Δ $PM_{2.5}$ concentrations predicted for Winter from the SIP Case

	Ground-level $PM_{2.5}$	
Case	**Max 1-hr**	**Max 24-hr**
2A	-5.87 ug/m^3	-1.50 ug/m^3
2C	-5.75 ug/m^3	-1.31 ug/m^3
2D	-5.75 ug/m^3	-1.43 ug/m^3
3A	-5.75 ug/m^3	-1.42 ug/m^3
4A	-5.75 ug/m^3	-1.41 ug/m^3

Conclusions

Moving forward, the use of advanced technologies including advanced CNG engines in MDV and HDV that reduce emissions from current diesel and gasoline vehicles can reduce GHG and improve AQ in California. The following section presents key conclusions from this work.

A range of prospective GHG impacts varying in magnitude and controlled by characteristics of the utilized life cycle (e.g. fuel production pathways, complimentary technologies, conversion methods) are possible. The carbon intensities estimated here are representative of average values across pathways, and therefore provide a relatively basic estimation of GHG emissions. Therefore, the results for GHG emissions should be interpreted as a general representation that provides useful insight on potential trends associated with the use of biomass and biogas resources as HDV fuel.

Considering the significant increase in advanced CNG vehicles in alternative cases, the use of advanced CNG engines can provide reductions in GHG for HDV and MDV although reductions are moderate if all CNG is assumed to come from conventional fossil resources, i.e., 14 to 26% if the baseline fleet is composed of less efficient diesel and gasoline technologies. For the more realistic assumption of a cleaner mix of technologies and fuels, the reduction is less (6 to 9%) if only fossil natural gas meets CNG demand. For the high total CNG demand estimated for the majority of Base alternative cases, in-state resources are unable to entirely meet CNG demand and some portion (5 to 35%) be met with fossil CNG. Conversely, demand in the majority of the cleaner technology mix SIP cases can be met with renewable CNG from in-state resources. However, this requires the availability of significant amounts of CNG from solid biomass resources, and that use by HDV and MDV be prioritized over other end-uses. When considering only RNG pathways from LFG and ADG from WWTP, dairies, and MSW (i.e., no biomass gasification) in-state resource can provide 22 to 30% of total CNG.

If renewable pathways provide RNG and RSNG to fuel vehicles GHG reductions can be increased – although in-state RNG resources are limited. The use of RNG can provide GHG reductions in alternative cases of 16 to 34% for the Base Cases and 9 to 18% for the SIP Cases depending on the assumed resource mix. If the gasification of solid biomass is included to provide RSNG reductions could reach 42 to 62% for the Base Case to 34 to 53% for the SIP Cases. The largest reductions in GHG occur for the Base Case scenarios, however it is likely the MDV and HDV fleet will be comprised of cleaner technologies due to AQ regulations and other drivers. For the more realistic assumption of a cleaner mix of technologies and fuels in the SIP Case, while the overall reduction is decreased due to the presence of electric and hydrogen vehicles, the demand for CNG can be met entirely by in-state RNG resources. Scenarios achieving the largest GHG reductions were associated with significant amounts of available RSNG produced through the gasification of biomass. Such a pathway is not currently commercially viable and will require technological and economic advancement prior to widespread deployment. The results highlight the importance of advancing solid biomass pathways for renewable transportation fuel and the relatively lesser availability of in-state RNG.

The use of advanced CNG engines provide reductions in NO_x emissions that reduce ground-level concentrations of ozone and $PM_{2.5}$. Reductions in ground-level ozone in summer range from -0.97 ppb to -2.77 ppb in a future where HDV and MDV technology does not significantly advance (Base Case) and from 1.16 to 1.25 ppb in a future with an assumed increases in advanced, lower emitting technologies and fuels (SIP Case). Similarly, reductions in summer $PM_{2.5}$ are predicted between -0.52 ug/m^3 to -0.60 ug/m^3 for the Base Case and -0.50 ug/m^3 to -0.51 ug/m^3 for the SIP Case. Impacts on $PM_{2.5}$ are particularly large in winter, with predicted reductions ranging from -2.71 ug/m^3 to -3.41 ug/m^3 for the Base Case and -1.41 ug/m^3 to -1.50 ug/m^3 for the SIP Case. Additionally, as a result of the relatively moderate ozone concentrations modeled for the summer episode the observed reductions should be considered less than what may be observed for episodes of higher concentration. Therefore, it is appropriate that the summer ozone impacts should be considered a moderate to lower bound for potential impacts.

These impacts are most notable in regions that currently experience unhealthy levels of air pollution including the SoCAB, Central Valley, S.F. Bay Area, and Greater Sacramento area. Increasing the deployment of advanced CNG vehicles can achieve benefits from a future characterized by moderate advancement in MDV and HDV technologies; and from the supposition of more aggressive deployment of advanced technology portfolios in California to meet regulatory standards. Therefore, the increasing the deployment of advanced CNG vehicles above levels that are currently expected or targeted can offer important AQ benefits by reducing atmospheric pollutant concentrations in currently affected areas of the State.

Impacts on ozone are driven by the significant reductions in emitted NO_x, evident by the trends in predicted ozone concentrations. Predicted reductions in $PM_{2.5}$ are also influenced by secondary PM mechanisms associated with emissions of NO_x [28], evident in Summer and Winter Base and Winter SIP trends as directly emitted $PM_{2.5}$ and ROG are assumed to be minor compared to the substantial differences in emitted NO_x. Conversely, despite significant differences in NO_x emissions between cases, summer SIP $PM_{2.5}$ levels remain relatively constant. This could be a result of a threshold for secondary mechanisms associated with nitrate $PM_{2.5}$ levels in summer as the SIP Case incurs significantly less total NO_x emissions. Additionally, non-exhaust traffic-related emissions [29] including PM generated from brake and tire wear are assumed to be equivalent amongst vehicle technologies considered. Direct $PM_{2.5}$ emissions are assumed to be reduced slightly for advanced CNG engines relative to advanced diesel and gasoline engines in terms of total mass. However, the chemical composition of emitted PM is likely to be substantially different. The chemical composition of PM is a direct determinant of human health impacts [30, 31], and thus exposure to $PM_{2.5}$ generated from advanced CNG engines may have dissimilar health impacts compared to exposure to diesel or gasoline generated $PM_{2.5}$ [32]. This is an issue that would benefit from further study including toxicological research.

Impacts on $PM_{2.5}$ highlight the importance of seasonal variation as equivalent emission reductions in both quantity and spatial signature achieve significant differences in both the quantity and spatial signature of resulting $PM_{2.5}$ improvements. In particular, improvements predicted for the winter modeling period are sizeable, i.e., exceeding -1.50 ug/m^3 to -3.41 ug/m^3 depending on the composition of the HDV and MDV fleet. Peak reductions are widespread throughout the Central Valley – a location that suffers from winter-time $PM_{2.5}$ levels above health-based standards. Impacts predicted for summer conditions also reach significant levels, however the spatial occurrence of peak impacts differs from the winter period, with peak concentration reductions predicted for the SoCAB, and others areas of note including a different portion of the Central Valley.

When considering the impact of technology shifts for in-state vehicles relative to vehicles registered out-of-state or internationally, the results of Case 2D relative to the SIP are relevant. Within Case 2D, the use of advanced CNG engines for in-state MDV and HDV could improve summer ozone by 1.18 ppb and $PM_{2.5}$ by -0.50 ug/m^3 in summer and 1.43 ug/m^3. These results demonstrate that shifts to advanced CNG engines are beneficial to AQ even if the challenge of instigating shifts for vehicles outside of California prevents significant penetration levels of advanced technologies.

Summary

The following are key conclusions from this work:

- Expanding the deployment of advanced CNG MDV and HDV can reduce summer ground-level ozone concentrations in key regions of California including the SoCAB, Central Valley, S.F. Bay Area, and Sacramento. Reductions could exceed -1.25 to -3.77 ppb depending on the evolution of advanced vehicle technologies within HDV and MDV fleets.
- Advanced CNG MDV and HDV can also achieve reductions in ground-level $PM_{2.5}$ in key regions of California including the Central Valley and SoCAB. Impacts in winter are particularly notable with some areas experiencing reductions exceeding -1.50 to -3.41 ug/m^3 in the Central Valley. Highlighting the seasonal nature of PM impacts, predicted reductions for summer peak in the SoCAB at -0.51 to -0.60 ug/m^3.
- The use of advanced CNG engines for in-state HDV (approximately 60% of total HDV) could improve summer ozone by 1.18 ppb and $PM_{2.5}$ by -0.50 ug/m^3 in summer and 1.43 ug/m^3. This is notable due to challenges associated with forcing technology shifts for out-of-state or international HVD and MDV.
- The largest AQ benefits are associated with reducing emissions from HDV. The results highlight the importance of continuing the development and advancing the deployment of advanced CNG engines in larger vehicle classes.
- While the mass of emitted $PM_{2.5}$ is assumed to be similar for advanced CNG engines relative to advanced diesel and gasoline engines, the chemical composition of emitted PM may differ substantially with implications for human health impacts. This is an issue that would benefit from further study, including toxicological research.
- In-state RNG pathways can meet the CNG demand estimated for both baseline cases, including the less optimistic case of advanced technology deployment (Base) and more optimistic case including additional alternative technologies and fuels (SIP). The SIP Case is representative of the most plausible outcome for the sector in 2035 and it is likely demand could be met entirely with in-state RNG in 2035 if levels of advanced CNG increase moderately within HDV and MDV fleets.
- For the high total CNG demand estimated for the majority of Base alternative cases, in-state resources are unable to entirely meet CNG demand and some portion (5 to 35%) be met with fossil CNG. Conversely, demand in the majority of the cleaner technology mix cases can be met with renewable CNG from in-state resources. However, this requires the availability of significant amounts of CNG from solid biomass resources, and that use by HDV and MDV be prioritized over other end-uses. When considering only RNG pathways from LFG and ADG from WWTP, dairies, and MSW (i.e., no biomass gasification) in-state resource can provide 22 to 30% of total CNG. The results highlight

the importance of advancing solid biomass pathways for renewable transportation fuel and the relatively lesser availability of in-state RNG.

- Advanced CNG HDV and MDV can moderately reduce GHG emissions if fossil natural gas is used (14 to 26%), particularly if the baseline fleet is composed of less efficient diesel and gasoline technologies. For the more realistic assumption of a cleaner mix of technologies and fuels, the reduction is less (6 to 9%) if only fossil natural gas meets CNG demand.
- The use of RNG can provide GHG reductions in alternative cases of 16 to 34% for the Base Cases and 9 to 18% for the SIP Cases depending on the assumed resource mix. If the gasification of solid biomass is included to provide RSNG reductions could reach 42 to 62% for the Base Case to 34 to 53% for the SIP Cases.

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