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TECHNICAL PAPER

Benefits of near-zero freight: The air quality and health impacts of low-NO_x compressed natural gas trucks

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ABSTRACT

The use of low-NOx compressed natural gas (CNG) medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs) has the potential to significantly reduce NO_x emissions and yield improvements in regional air quality. However, the extent of air quality improvement depends on many factors including future levels of vehicle deployment, the evolution of emissions from other sources, and meteorology. An analysis of the impacts requires modeling the atmosphere to account for both primary and secondary air pollutants, and the use of health impact assessment tools to map air quality changes into quantifiable metrics of human health. Here, we quantify and compare the air quality and health impacts associated with the deployment of low-NO_x CNG engines to power future MDV and HDV fleets in California relative to both a business-as-usual and a more advanced fleet composition. The results project that reductions in summer ground-level ozone could reach 13 ppb when compared to a baseline fleet of diesel and gasoline HDV and MDV and could reach 6 ppb when compared to a cleaner fleet that includes some zero-emission vehicles and fuels. Similarly, for all CNG cases considered reductions in $PM_{2.5}$ are predicted to range from 1.2 ug/m^3 to 2.7 ug/m^3 for a summer episode and from 3.1 ug/m^3 to approximately 7.8 ug/m^3 for a winter episode. These improvements yield short-term health benefits equivalent to \$47 to \$56 million in summer and \$38 to \$43 million in winter during episodes conducive to poor air quality. Additionally, the use of zero emission vehicle options such as battery electric and hydrogen fuel cell trucks could achieve approximately 25% to 31% higher benefits for an equivalent fleet penetration level due to the additional emission reductions achieved.

Implications: The paper provides a quantitative estimate of the air quality and human health benefits that can be achieved through the use of novel compressed natural gas engines (i.e., low-NO_x CNG) in medium- and heavy-duty vehicles and provide a comparison with zero emission vehicles. Thus, our findings will provide support for policy development seeking to transform the trucking sector to meet clean air and climate goals given the current struggle policymakers have with selecting between alternative truck technologies due to variance in factors like cost and technical maturity.

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Introduction

California environmental quality targets require mobile sources to attain reductions in criteria air pollutants to ensure compliance with federal air quality (AQ) standards, and reductions in greenhouse gases (GHG) established under AB 32 (California's 2017; Climate Change Scoping Plan 2017; California Air Resources Board 2018a). As an integral part of the on-road goods movement sector, medium- (MDV) and heavy-duty vehicles (HDV) provide important services to California's economy, but also represent a leading source of air pollution with subsequent deleterious human health effects (Brown 2016; Mobile Source Strategy 2016). For example, MDV and HDV are responsible for approximately 20% of NO_x emissions in the state (CARB 2017a). This results from the current reliance on vehicles powered by the combustion of petroleum fuels, including diesel and gasoline (California Energy Commission and CEC 2016). The combustion of diesel fuel is particularly concerning from a human health standpoint as it results in the generation of damaging pollutants including oxides of nitrogen (NO_x), particulate matter (PM), and toxic air contaminants (Kennedy 2007; Ris 2007). Therefore, transitions from petroleum-fueled vehicles to cleaner, lower emitting technologies and fuels will be necessary within the MDV and HDV sectors in California.

MDV and HDV are highly diverse. Thus, and a range of alternative vehicles are being considered, including

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Supplemental data for this paper can be accessed on the publisher's website.

the use of electricity within battery electric trucks and hydrogen within fuel cell powered vehicles, both of which achieve zero tail pipe emissions (here within referred to as zero emission vehicles (ZEV)). However, the technical feasibility and currently high costs associated with these options raise questions regarding the near-term suitability of hydrogen and electricity to achieve significant reductions in emissions from the trucking sector (Couch et al. 2019). Additionally, an alternative technology being considered for both applications is the low-NO_x compressed natural gas (CNG) engine, which achieves significant reductions in NO_x and moderate reductions in other pollutants including PM (Quiros et al. 2016). Low-NO_x CNG stoichiometric spark ignition engines significantly reduce NO_x emissions by utilizing a systems approach combining advanced three-way catalysts with engine management strategies (California Air Resources Board 2015). These engines have been demonstrated to operate with NO_x emissions below the CARB optional low NO_x standard (0.02 g/bhp-hr) and averaged between 0.0012 and 0.02 g/bhp-hr, well below baseline diesel engines (Johnson 2018). Various engine manufacturers, including Cummins Westport and Roush Clean, have developed CNG engines ranging from 6.7 to 12 liter (L) that are commercially available and have been certified to one of the optional reduced NO_x standards for on-road heavy-duty engines adopted by the California Air Resources Board (CARB) (California Air Resources Board 2017a). Therefore, low-NO_x CNG engines represent a technology that can be deployed near-term to mitigate the pollutant emissions and AQ impacts of MDV and HDV.

However, understanding how changes in precursor emissions including NO_x and reactive organic gases (ROG) impact ambient pollutant concentrations is complex and requires modeling of the atmosphere, rather than a simple understanding of total emission reductions. Deployment of low-NO_x CNG engines to displace current MDV and HDV will impact pollutant emissions quantitatively, spatially, temporally, and in chemical composition; all of which subsequently influence ambient concentrations of primary and secondary air pollutant species. Further, the development and outcome of secondary air pollutants are controlled by multifaceted, non-linear atmospheric processes (Finlayson-Pitts 1997). For example, lower levels of ozone and $PM_{2.5}$ (from reductions in NO_x) would be expected from low-NOx CNG replacement of diesel vehicles. However, without atmospheric modeling the quantification, spatial patterns, and temporal periods of such reductions cannot be determined. Therefore, detailed atmospheric models accounting for both chemistry and transport must be used to resolve spatial and temporal distribution of pollutant concentrations to assess comprehensively how alternative fueled vehicles may impact AQ in California. Finally, the impacts on AQ are translated into human health impacts, and then those impacts are monetized to provide a quantification of the health economic benefits. The results can assist policymakers in better understanding the implications of AQ improvements in the design of regulations that maximize human health benefits.

A significant body of research exists with regard to the emissions impact of CNG MDV and HDV. The overall AQ impacts of MDV and HDV have been quantified and compared to other on-road sectors (Mac Kinnon et al. 2019), including the potential use of ZEV (Mac Kinnon et al. 2016). The AQ and human health benefits of deploying alternative vehicle technologies and other emission reduction strategies in a portfolio approach have been estimated for the U.S. (Pan et al. 2019). The performance and criteria pollutant emissions of in-use CNG engines relative to conventional petroleum fueled engines have been reported in a large number of studies (Quiros et al. 2016; Hesterberg, Lapin, and Bunn 2008; Thiruvengadam et al. 2015; Korakianitis et al. 2011; Lanni et al. 2003; McCormick et al. 1999; McTaggart-Cowan et al. 2006). Specifically, the reduction of air emissions of compounds representing human health concerns has been noted (Kado et al. 2005) (Agarwal et al. 2018). The health benefits of AQ improvements from transitions to CNG in transportation for a large urban area have been modeled, however the study only considered CNG-fueled buses and reported impacts solely for $PM_{2.5}$ (Mena-Carrasco et al. 2012). Observation data has also been used to quantify the AQ benefits of CNG replacement of diesel buses in a mega city (Delhi) (Goyal 2003). Similarly, studies have assessed both the direct and lifecycle emissions of greenhouse gases (GHG) for CNG pathways relative to diesel and gasoline (López et al. 2009; Camuzeaux et al. 2015; Tong, Jaramillo, and Azevedo 2015; Dominguez-Faus 2016). However, no study has reported AQ impacts via comprehensive assessment of primary and secondary air pollutants and associated health impacts for a range of scenarios representing large-scale build-out of CNG engines in all vocations of the MDV and HDV sectors at the state level. Furthermore, all of these studies consider conventional CNG engines that do not represent the improved emission performance of the low-NO_x engines.

Therefore, the regional AQ and human health implications from the large-scale deployment of low-NO_x CNG engines are currently unclear and, for the first time, we quantify and compare the impacts from using low-NO_x CNG engines to power future MDV and HDV fleets in California. We consider the impacts of low-NO_x CNG trucks within the initial framework of both a conservative and an optimistic outcome for alternative vehicles as it provides insight into potential benefits across a span of potential evolutionary pathways for the California MDV and HDV fleets. We assess the emission reductions attainable through replacement of conventionally fueled vehicles in 2035, and how emission impacts translate to changes in atmospheric primary and secondary pollutant concentrations via a photochemical AQ model. We then quantify the impacts of AQ changes on human health through the use of a health impact assessment tool to determine the potential monetary value of avoided pollution-induced health incidences. We focus on California as it consistently experiences degraded AQ in regions supporting large population centers yielding serious risks to human health (CARB 2017b) and is aggressively pursuing the deployment of alternative technologies in pursuit of emission reductions from MDV and HDV (Mobile Source Strategy 2016; Brown 2016). Additionally, while reduced from current combustion-based vehicles, tail pipe emissions from low-NO_x CNG are higher than from ZEV (which are also under consideration for MDV and HDV vocations) and we include a ZEV scenario to provide comparison of this tradeoff. Therefore, results from this work provide insight into the potential tradeoffs associated with the immediate commercial readiness of the low-NO_x CNG relative to the complete reduction in tailpipe emissions from ZEV.

Methodology

Scenario development

We develop scenarios of low-NO_x CNG engines in the MDV and HDV within California for the year 2035. The year 2035 is selected because 1) it provides a reasonable horizon for alternative vehicle deployment to reach impactful levels due to fleet-turnover and 2) projected emissions for other sources were available to that year. The scenarios are designed to span the range of potential fleet penetrations with an optimistic stance on the displacement of baseline diesel and gasoline engines. Furthermore, scenarios are constructed to capture other issues associated with alternative fueled vehicles, including the ability of California to regulate emissions from vehicles registered out-of-state.

Cummins Westport's 8.9 L SI CNG engine has been certified by the U.S. Environmental Protection Agency (EPA) and the ARB to a 0.027 g per brake horsepower-hour (g/bhp-hr) optional NO_X standard, and both Cummins Westport and Roush Cleantech have 6 L engines certified to the 0.1 g/bhp-hr standard (California Air Resources Board 2018b). Cummins Westport also has an 11.9 L engine certified to the 0.02 g/bhp-hr standard for Class 8 truck and bus applications (33,000-plus pounds gross vehicle weight) (Zwissler and Ptucha 2018). The 6.7 L, 6.8 L, and 8.9 L engines are applicable for MDV including trucks, urban transit, and school buses, and refuse hauler applications. The Cummins Westport 11.9 L engine is applicable to on-road HDV applications including long and regional haul trucks and tractors, vocational and transit, school bus, and refuse applications. 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 (Next Generation Heavy-Duty Natural Gas Engines Fueled By Renewable Natural Gas). Therefore, we assume that low-NO_x CNG engines will be available and suitable for all MDV and HDV vocations in 2035.

In 2013, the ARB established optional low NO_x standards for heavy-duty engines. As of February 2020, no diesel engines are certified, and only natural gas and LPG engines have been certified (U.S. Environmental Protection Agency 2020). For example, the 11.9 L engine was certified on a chassis dynamometer across a range of duty cycle representative of typical urban operation including drayage port cycles, the urban dynamometer driving schedule, and three cycles designed by CARB (Johnson 2018). While a full review of the emission factors of the various CNG engines is outside the scope of this work, additional information can be found in References (Johnson 2018; California Air Resources Board 2018b; Next Generation Heavy-Duty Natural Gas Engines Fueled By Renewable Natural Gas 0000; US Environmental Protection Agency 2020).

Vision model

The Heavy Duty Vehicle Module within the Vision Scenario Planning Model version 2.1 is used to develop scenario representative of the integration of low-NO_x CNG engines into the MDV and HDV population for the year 2035. Vision was developed by CARB and allows users to conduct multi-pollutant assessments for the transportation sector system-wide in California accounting for vehicle sales, activity, technologies, fuels, and efficiencies to estimate energy demands (California Air Resources Board 2017b). The Vision HDV module generates two sets of baseline emission databases by design. The first considers that the only emission control regulations are those the current regulations set in place, i.e., the Base Case. In comparison, the State Implementation Plan (SIP) Case includes the controls and regulations described in California's SIP document which affects the HDV population and results in MDV and HDV fleets composed of lower emitting technologies than the Base Case overall (the measures assumed for each case are provided in the SI). It is important to note that the Vision projections are from 2017, and thus do not account for several recent regulatory statutes with implications for future MDV and HDV fleets including the CARB Advanced Clean Trucks Regulation and the Heavy-Duty Engine and Vehicle Omnibus Regulation. Therefore, the baseline fleet mixes estimated using Vision are likely to be higher emitting than current regulations dictate.

Using the two baseline datasets (Base and SIP) as starting points, additional scenarios are developed to assess the increased implementation of low-NO_x CNG engines across MDV and HDV categories by displacement of gasoline or diesel engines. While a small penetration of additional alternative technologies is assumed for some of the cases, including hydrogen fuel cell and battery electric vehicles, in this work low-NO_x CNG vehicles are the predominant technology to replace diesel and gasoline vehicles. The scenarios shown in Table 1 assume mid- (50%) and high (100%) optimism regarding CNG fleet penetration levels with equivalent deployment across all vocations for the 50% cases. The 100% adoption of low-NOx CNG (Case 1B) is relevant to both the Base and SIP Cases and is compared to both to determine the upper bounds for vehicle utilization. While the majority of cases are designed to span vehicle deployment outcomes, two cases from the SIP Case are designed to assess the impact of additional considerations. First, Case 2C assumes complete deployment only for HDV vocations expected to be the most feasible for low-NO_x CNG technologies (shown in Table SI 1) to consider impacts if low-NO_x CNG engines do not become commercially developed for all vocations, resulting in an HDV penetration of 41%. Second, Case 2D assumes deployment only for HDV registered in the state to consider the impact of challenges associated with the regulation of out-of-state and international vehicles, resulting in an HDV CNG fraction of 60%. In addition, a case is considered assuming complete deployment of ZEV (100 ZEV) within MDV and HDV for comparison with the potential impacts of using ZEV, such as battery electric and hydrogen fuel cell vehicles.

Depending on the scenario, we project vehicle population and daily vehicle miles traveled (VMT) of HDV and MDV by technology type to 2035 using Vision. Shown in Figure 1, in Case 1B all MDV and HDV transition to low-NO_x CNG from diesel and gasoline technologies, representing the upper bound for possible impacts. Conversely, Figure 2 shows the evolution of the MDV and HDV fleets to 2035 for Case 2D, which assumes all in-state HDV transition to low-NO_x CNG. Case 2D is constructed based on the SIP Case, which assumes a cleaner mix of baseline technologies than the Base Case including CNG, low-NO_x standard diesel, and gasoline. Additionally, battery electric and hydrogen fuel cell vehicles in last mile delivery applications are included although at a low total percentage. Case 2D provides a more conservative and realistic estimate for low-NO_x CNG impacts as the SIP Case is designed to provide emission reductions needed to meet AQ mandates, and in-state vehicles may be more straightforward to encourage shifts to low-NO_x CNG (relative to out-of-state and international vehicles).

Emission projection and resolution

Baseline AQ is established by projecting emissions from the 2012 California Air Resources Board inventory (CARB 2013) for all sources excluding MDV and HDV (e.g., industry, off-road transportation, power generation, etc.) from the California Air Resources Board's CEPAM: 2016 SIP – Standard Emission Tool (CARB 2017a). For MDV and HDV, total emissions of criteria pollutants required for AQ modeling, including NO_x, PM in 10 ug (PM_{10}) and $PM_{2.5}$, reactive organic gases (ROG), and CO are obtained from Vision. For NO_x, an

Table 1. Name and description of each scenario considered for this study including the total fleet penetration of low-NO_x CNG engines.

Scenario	Case origin	HDV assumption [% of fleet low-NO_x CNG]	MDV assumption [% of fleet low-NO_x CNG]
Base	–	2035 diesel and gasoline engines meeting 2017 regulations	2035 diesel and gasoline engines meeting 2017 regulations
SIP	Base	Measures in SIP document	Measures in SIP document
1B	Base/SIP	100%	100%
2A	SIP	100%	50%
2B	Base	100%	50%
2 C	SIP	All likely vehicles (41%)	50%
2D	SIP	All In-state vehicles (60%)	50%
3A	SIP	50%	50%
3B	Base	50%	100%
4B	Base	50%	50%
100 ZEV	N/A	100% Zero-emission Vehicles	100% Zero-emission Vehicles

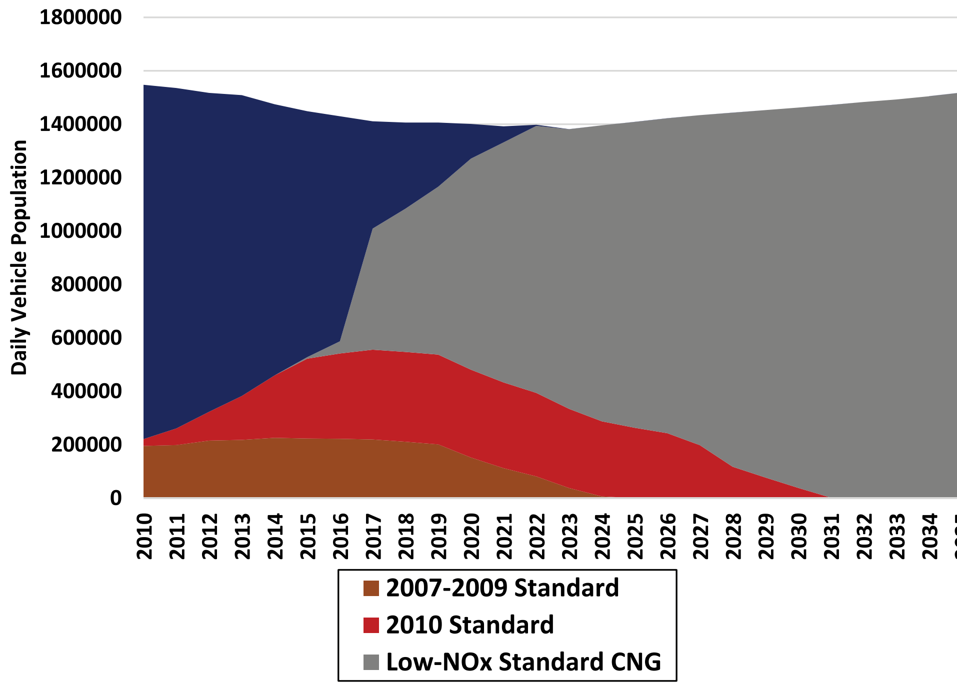

Figure 1. Daily vehicle population of MDV and HDV to 2035 in Case 1B.

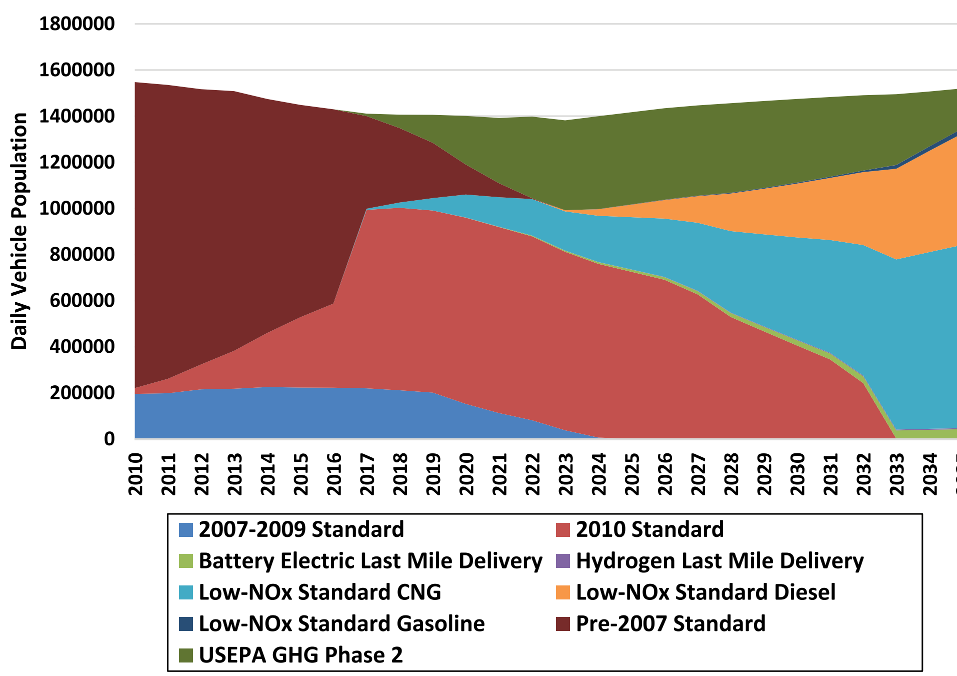

Figure 2. Daily vehicle population of MDV and HDV to 2035 in Case 2D.

NO_2/NO ratio of 0.174 is assumed. It should be noted that upstream pollutant emissions for vehicle fueling pathways are not considered in this work and only direct vehicle tailpipe and evaporative emissions are modified. Emission representative of each case is applied and resolved in space and time using the Sparse Matrix Operator Kernel Emissions (SMOKE) modeling system (US EPA 2017). 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.

The vehicles are assumed to be equally distributed within the current spatial and temporal patterns of MDV and HDV throughout California. Reductions are associated with current transportation networks within California including the locations of vehicle activity, with locations of peak reductions in urban areas supporting high levels of MDV and HDV activity including the SoCAB, Central Valley, and the San Francisco (S.F.) Bay Area. These areas have particular importance in regard to AQ improvements due to preexisting degraded AQ and the existence of large populations with implication for health impacts (Zhu et al. 2019).

Air quality modeling

We conduct simulations of atmospheric chemistry and transport via the Community Multi-scale Air Quality model (CMAQ, v5.2) to establish fully developed distributions of atmospheric concentrations of pollutants of interest, including ground-level ozone and $PM_{2.5}$ (US EPA Office of Research and Development 2017). CMAQ is a widely known model used for various AQ assessment needs, including regulatory compliance and atmospheric research associated with tropospheric ozone, PM, acid deposition, and visibility (Foley et al. 2015; Foley et al. 2010). For gas-phase chemistry, we use the SAPRC-07 chemical mechanism (Carter 2010) and the AERO6 module to provide aerosol dynamics (Pye et al. 2013). The model domain is the same as Mac Kinnon et al. (2019), covering the entire state of California with 4 km × 4 km horizontal resolution. Boundary conditions are generated via the Model for Ozone and Related Chemical Tracers (Mozart v4.0) (Emmons et al. 2010). We generate meteorological input data for the modeling period through the Advanced Research Weather Research and Forecasting Model (WRF-ARW, 3.7), with the MODIS land use database (Friedl et al. 2010). Baseline meteorological conditions are obtained from the (Final) Operational Global Analysis data (National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce, National Center for Atmospheric Research, Computational and Information Systems Laboratory 2000). The boundary conditions and meteorology are held constant from 2012 to 2035; thus, impacts of transported pollution and climate change are not considered. We verify model performance by comparison with observational data from the U.S. EPA Air Quality System for hourly ozone and $PM_{2.5}$, with acceptable performance demonstrated through the criteria recommended in Reference (Emery et al. 2017). More details regarding the model performance can be found in the SI, and a complete report of statistical parameters is presented by Zhu et al. (2019).

The two pollutants considered to assess AQ for this work are $PM_{2.5}$ and ground-level ozone. Ozone is an important component of photochemical smog, and is not directly emitted but forms in the atmosphere during reactions between NO_x and ROG in the presence of sunlight (Finlayson-Pitts and Pitts 2000). $PM_{2.5}$ is both directly emitted and forms in the atmosphere during reactions of gaseous precursor emissions contributing to total atmospheric levels (Zhu et al. 2018)–(Kleeman 2008; Hallquist et al. 2009). Both represent current and historical air pollution concerns (many regions of California experience ambient levels in excess of state and federal health-based standards (CARB 2017b)) and are associated with human health detriments supported by a broad body of scientific literature (Dockery et al. 1993; Pope III and Dockery 2006; Jerrett et al. 2009). Therefore, ground-level concentrations of ozone and $PM_{2.5}$ serve as appropriate metrics in the evaluation of impacts associated with technological shifts targeting AQ improvements.

Modeling episodes seasonally is necessary to determine comprehensively impacts on ambient AQ. For example, ozone levels peak in the summer months as high ambient temperatures, enhanced solar radiation, and increased evaporative ROG emissions are favorable for the atmospheric chemical reactions driving ozone formation (Pusede et al. 2014). Here, 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) and winter episode (January 1–14). 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 (Carreras-Sospedra et al. 2006). The (July 8–21) period represents the highest ozone episode simulated within the Base Case. 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) of California and many regions of the Central Valley. The (January 1–14) period represents the highest $PM_{2.5}$ episode simulated within the Base Case. The first 3 days of each period are considered model spin up and excluded from the analysis of the results.

For consistency with ambient AQ standards, ground-level concentrations are reported as maximum daily 8-hr average ozone (MD8H) and 24-hr average $PM_{2.5}$ calculated by two different methods. First, to capture the peak AQ impacts, we calculate the largest MD8H ozone and 24-hr $PM_{2.5}$ average that occurs for each model grid cell for any averaging period within the 11-day period. This provides an understanding of the maximum possible impact that may be experienced. Second, to provide a marker of the general impact experienced throughout the entire 11-day episode, we calculate the average

MD8H ozone and 24-hr $PM_{2.5}$ experienced for each modeling grid cell. Following the methods of Zhu et al. (2019), we report ozone for the summer episode as California is well known to experience episodes of high ozone pollution during this period. In contrast, ozone concentrations in winter are generally below Federal National Ambient AQ standards (NAAQS) in California. For example, predicted levels for both the Base and SIP cases remain under the NAAQs and California standards for MD8H ozone of 70 parts per billion (ppb). Therefore, ozone is not reported here for the winter episode. We compute changes in concentration for $PM_{2.5}$ for both the summer and winter episodes as $PM_{2.5}$ pollution is a concern for human health during both seasons. Finally, concentrations are compared between the Base and the low-NO_x CNG Cases to derive the impacts.

Health impact assessment

Improvements in AQ benefit public health by reducing pollution-related incidence of mortality and morbidity, e. g., premature death, non-fatal heart attacks and strokes, and other adverse health effects. To quantify these health savings, we use the environmental Benefits Mapping and Analysis Program – Community Edition (BenMAP-CE) from the U.S. EPA (Sacks et al. 2018). For this work, BenMAP-CE is used to quantify benefits from improvements in ozone and $PM_{2.5}$ attained through low-NO_x CNG MDV and HDV deployment. The methods used follow those in the South Coast Air Quality Management District's (SCAQMD) Socioeconomic Report for the 2016 Air Quality Management Plan (AQMP) (Shen, Oliver, and Dabirian 2017). Population projections are based on Landscan data (ORNL 2016) and grown to 2035 using projections from the California Department of Finance which captures spatial expansion at the county level (California DOF 2017). Baseline incidence rates for mortality and morbidity are estimated from public administrative records where feasible, and projected from U.S. Census Bureau data (Industrial Economics 2016). Concentration-response and economic valuation functions are selected based on suggested criteria from a systematic review of the epidemiological literature (Industrial Economics and Lisa Robinson 2016; Industrial Economics and Lisa Robinson 2016). Though BenMAP-CE can be used to estimate long-term health impacts, such as those occurring from annual average $PM_{2.5}$ changes, impacts are reported here for short-term exposure to ozone and $PM_{2.5}$ (as appropriate for the modeled episode) due to intensive resource requirements necessary for simulating cases annually. It should be noted that the use of long-term health impact functions, e.g., those for annual PM, would result in notably higher valuations for avoided adverse health incidence.

Results and discussion

Criteria pollutant emission results

Direct emissions from low-NO_x CNG relative to diesel and gasoline equivalent vehicles calculated from the Vision Base Case are shown in Table 2. The use of CNG reduces NO_x by 96% from baseline diesel, 93% from diesel engines assumed to meet the EPA GHG 2 standards, and 20% relative to an advanced low-NO_x diesel engine. Low-NO_x CNG engines reduce emissions of ROG from baseline and advanced diesel engines by 17% to 52%. $PM_{2.5}$ emissions are more similar between technologies because (1) the assumption that future diesel vehicles require particulate filters reduce direct $PM_{2.5}$ from those sources and (2) $PM_{2.5}$ generated through brake and tire wear is assumed to be constant regardless of engine technology and fuel, i.e., CNG and ZEV generate equivalent emissions to baseline vehicles. Emissions of CO are higher for low-NO_X CNG compared to baseline and advanced diesel engines, but significantly lower than gasoline vehicles. These emissions compare reasonably well with other values reported in the literature (Quiros et al. 2016).

Figure 3 shows total HDV and MDV emissions for the Base Case and associated alternative cases including tailpipe for NO_x, tailpipe and evaporative for ROG, and tailpipe, tire wear, and brake wear for $PM_{2.5}$. The 100% low-NO_x CNG Case 1B achieves the lowest total emissions of NO_x, representing a 91% reduction from the Base Case, while Case 4B (50% low-NO_x in both HDV

Table 2. Direct emissions for advanced CNG, diesel, and gasoline vehicles estimated from the SIP in 2035 in grams per mile (g/mile).

Vehicle	NO_x [g/km]	ROG [g/km]	$PM_{2.5}$ [g/km]	CO [g/km]
Advanced CNG	0.066	0.033	0.034	0.430
Diesel (Baseline)	1.585	0.052	0.034	0.295
Diesel (EPA GHG 2)	1.033	0.069	0.032	0.560
Diesel (SIP)	0.083	0.040	0.030	0.166
Gasoline (Baseline)	0.575	0.473	0.030	2.723
Gasoline (SIP)	0.024	0.075	0.030	1.408

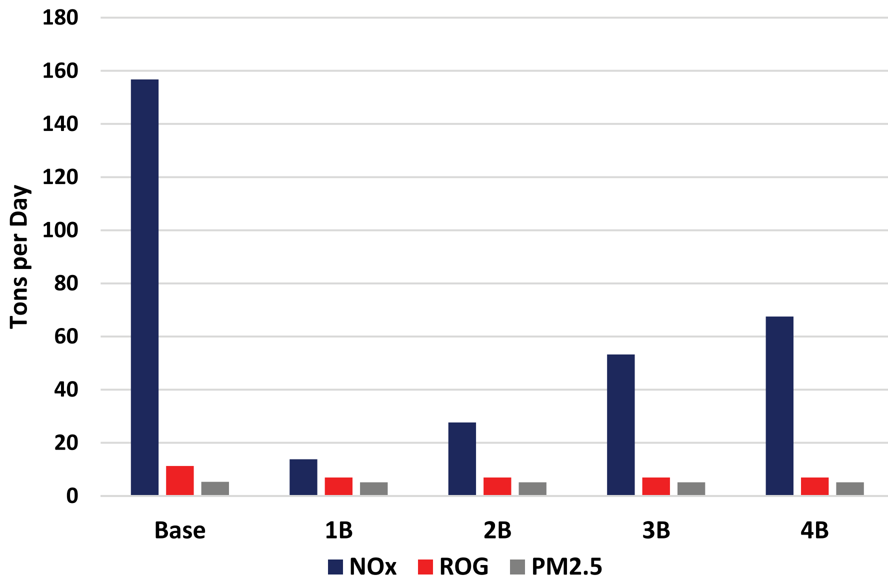

Figure 3. Total HDV and MDV emissions of NO_x, ROG, and $PM_{2.5}$ for the base case and alternative scenarios.

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). Emissions of ROG are reduced from the Base Case for all Cases, exceeding 38% and 97% reductions, respectively. Contrastingly, emissions of $PM_{2.5}$ are similar both between cases and the Base Case, and between the cases themselves.

Figure 4 shows total HDV and MDV emissions for the SIP Case and the alternative cases developed from the SIP Case. 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. Case 1B reduces NO_x from the SIP case by an additional 81%, demonstrating the ability of low-NO_x CNG vehicles to further reduce NO_x emissions even within a more advanced vehicle technology portfolio. Case 2A results in the next highest reduction of 75%, followed by Case 2D (71%) and Case 2 C (65%). As with the Base Case, reductions in ROG from the SIP Case are significant, but differences across cases are minor, and $PM_{2.5}$ is only modestly impacted.

Air quality results

Baseline air quality in the Base and SIP Cases

The absolute concentrations predicted for both the Base Case and the SIP Case serve as the baseline for comparison with the alternative cases and are shown in the SI.

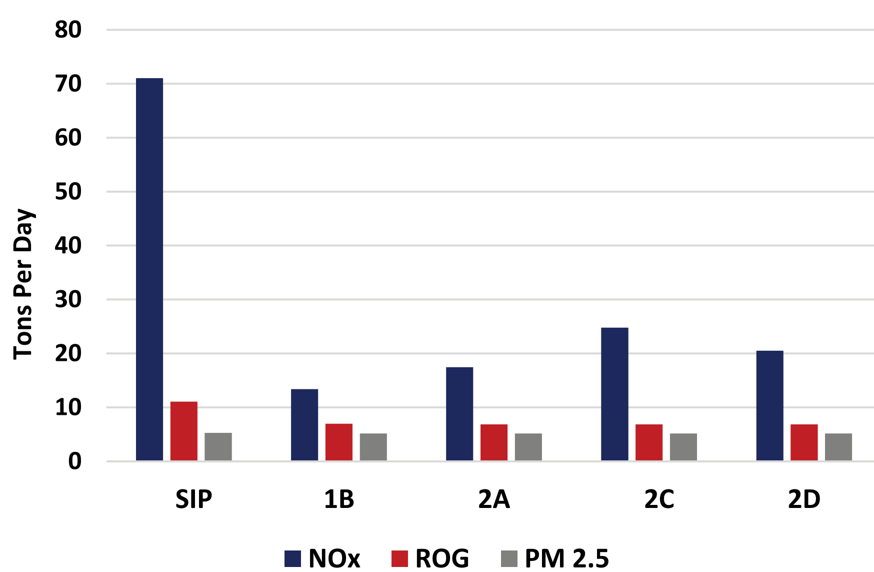

Figure 4. Total HDV and MDV emissions of NOx, ROG, and $PM_{2.5}$ for the SIP case and alternative scenarios.

In the Base Case, high MD8H ozone concentrations are observed in the SoCAB, Central Valley, San Francisco Bay Area (SFBA), and greater Sacramento, with a peak concentration of 133 ppb occurring in the eastern portions of the major urban areas encompassing SoCAB. During the summer period, high 24-hr average $PM_{2.5}$ concentrations are most prominent throughout the Central Valley potentially exceeding 100 ug/m^3, with regions of elevated $PM_{2.5}$ also occurring north of Sacramento, and SoCAB. For the winter period, peak $PM_{2.5}$ reaching 62.7 ug/m^3 in the northern portion of the Central Valley, with high concentrations predicted for greater Sacramento, SFBA, SoCAB, and San Diego. In the SIP Case, ozone and $PM_{2.5}$ concentrations are reduced from the Base Case due to the assumed cleaner technology portfolio within MDV and HDV. MD8H ozone concentrations reach 123 ppb and are comparable spatially to those for the Base Case. Similarly, for the summer episode 24-hr $PM_{2.5}$ concentrations exceed 98 ug/m^3 and 58 ug/m^3 in the winter episode.

Air quality impacts for the cases developed from the Base Case

Figure SI 5 displays the differences in peak MD8H ozone between the Base Case and the related alternative cases. Quantitatively, peak impacts correspond to NO_x emission trends with reductions for the most aggressive adoption within Case 1B exceeding −13.0 ppb, while reductions from the least aggressive adoption with Case 4B reaching −5.8 ppb (Table 3). These improvements are significant, and represent the maximum possible improvement occurring during an episode of high pollution as the meteorological conditions were selected to represent. When MD8H ozone changes are averaged across the 11-day period, reductions ranging from −5.8 to −3.6 ppb are predicted with similar trends across the cases. The most pronounced impacts occur in the eastern portions of SoCAB notable as experiencing the highest ambient ozone levels in the U.S. and supporting large population centers. Important reductions are also predicted throughout the Central Valley, SFBA, greater Sacramento, and San Diego.

Peak differences of $PM_{2.5}$ during the summer range from −1.65 ug/m^3 to −2.71 ug/m^3 for the cases considered, following ozone trends (Table 3). Figure SI 6 shows that reducing emissions from MDV and HDV reduces $PM_{2.5}$ with areas of peak impact corresponding to locations downwind of vehicle activity along the major transportation corridors in the Central Valley. Similarly, areas downwind of urban areas supporting large numbers of vehicles within the SoCAB and greater Sacramento experience benefits. Spatially, winter $PM_{2.5}$ impacts follow similar trends to those for summer with maximum impacts widespread throughout the Central Valley (Figure SI 7). However, the magnitude of the reductions is significantly increased from summer, with peak differences between −5.0 ug/m^3 and −7.81 ug/m^3 (Table 3). These values are significant given the current National Ambient Air Quality Standards for MD8H ozone and 24-hr $PM_{2.5}$ are 70 ppb and 35 ug/m^3, respectively. Impacts on $PM_{2.5}$ between the cases are largely characterized by differences in NO_x emission reductions, which is indicative of the role of reductions in secondary $PM_{2.5}$ in ground-level concentrations as differences in direct emissions of $PM_{2.5}$ and ROG between the Cases are minor compared to those for NO_x. Additionally, the importance of NO_x as a driver of secondary $PM_{2.5}$ concentrations has been demonstrated in California (Zhu et al. 2019).

Air quality impacts for the cases developed from the SIP Case

The following section discusses the concentration differences predicted between the SIP Case, serving as a baseline, and the alternative cases constructed around the SIP Case. Figure 5 displays differences in MD8H ozone and Figure 6 winter $PM_{2.5}$ for the CNG cases relative to the SIP case, while the results for summer $PM_{2.5}$ are provided in the SI. Generally, the impacts are equivalent spatially to those discussed for the Base Case but are reduced in magnitude as the SIP Case yields lower baseline ozone and $PM_{2.5}$ due to reduced emissions from a cleaner MDV and HDV truck fleet (Table 4). Still, the improvements are important both quantitatively and

Table 3. Δ peak and average ozone and $PM_{2.5}$ predicted from the base case.

	Ground-level Ozone		Ground-level $PM_{2.5}$			
Case	Peak Summer MD8H [ppb]	Average Summer MD8H [ppb]	Peak Summer Max 24-hr [ug/m^3]	Avg. Summer Average 24-hr [ug/m^3]	Peak Winter Max 24-hr [ug/m^3]	Avg. Winter Average 24-hr [ug/m^3]
1B	−13.3	−5.6	−2.7	−0.1	−7.8	−0.3
2B	−11.7	−4.9	−2.4	−0.1	−7.1	−0.3
3B	−9.6	−4.1	−1.9	−0.1	−5.8	−0.2
4B	−5.84	−3.4	−1.6	−0.1	−5.0	−0.2

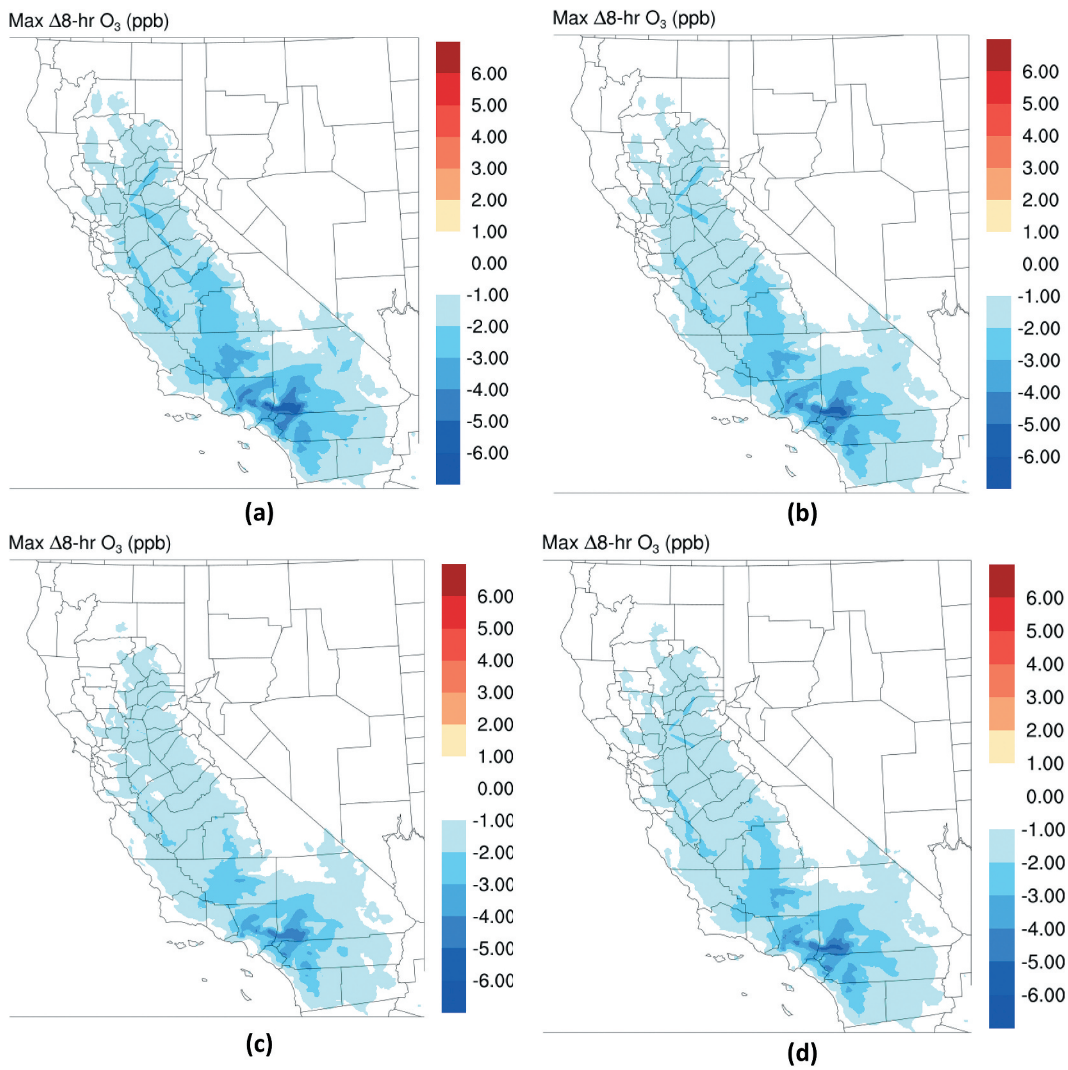

Figure 5. Peak differences in summer episode MD8H ozone between the SIP case and (a) Case 1B, (b) Case 2A, (c) Case 2C, and (d) Case 2D in ppb.

within the context of human health impacts as the peak impacts often coincide with highly populated regions currently experiencing poor AQ. Within this set of cases, the largest reduction occurs from Case 1B (100% low-NO_x CNG) and Case 2 C (41% HDV and 50% MDV low-NO_x CNG). Reductions in peak ozone range from −6.1 ppb in Case 1B to −5.4 in Case 2 C, and reductions in average ozone range from −1.2 to −1.4 ppb. Reductions in peak summer $PM_{2.5}$ range from −1.0 to −1.2 ug/m^3 and peak improvements in winter $PM_{2.5}$ range from −2.6 to −3.1 ug/m^3. The assumption of 100% of in-state vehicles in Case 2D results in approximately 60% of HDV and 50% of MDV transitioning to low-NO_x CNG engines and achieves notable AQ benefits despite the lack of replacement of out-of-state trucks.

While the maximum reductions do not appear to differ meaningfully between the cases, it should be considered that the spatial dimension of impact is not captured when using this metric, i.e., it represents the largest change experienced by one grid cell throughout the modeling domain. Demonstrating this, the difference in ozone and $PM_{2.5}$ between Case 1B and 2 C is shown in Figure SI 11, which are widespread and in important regions from an AQ standpoint. This further validates the need for the health impact assessment, which accounts for the spatial dimension of pollutant impacts by translating concentration changes into population exposure estimates.

Health impact assessment results

The following section presents the results from the health impact assessment quantifying and valuing differences in morbidity and mortality across the California population resulting from improvements in AQ. Results are presented for the SIP and the SIP-related Cases as

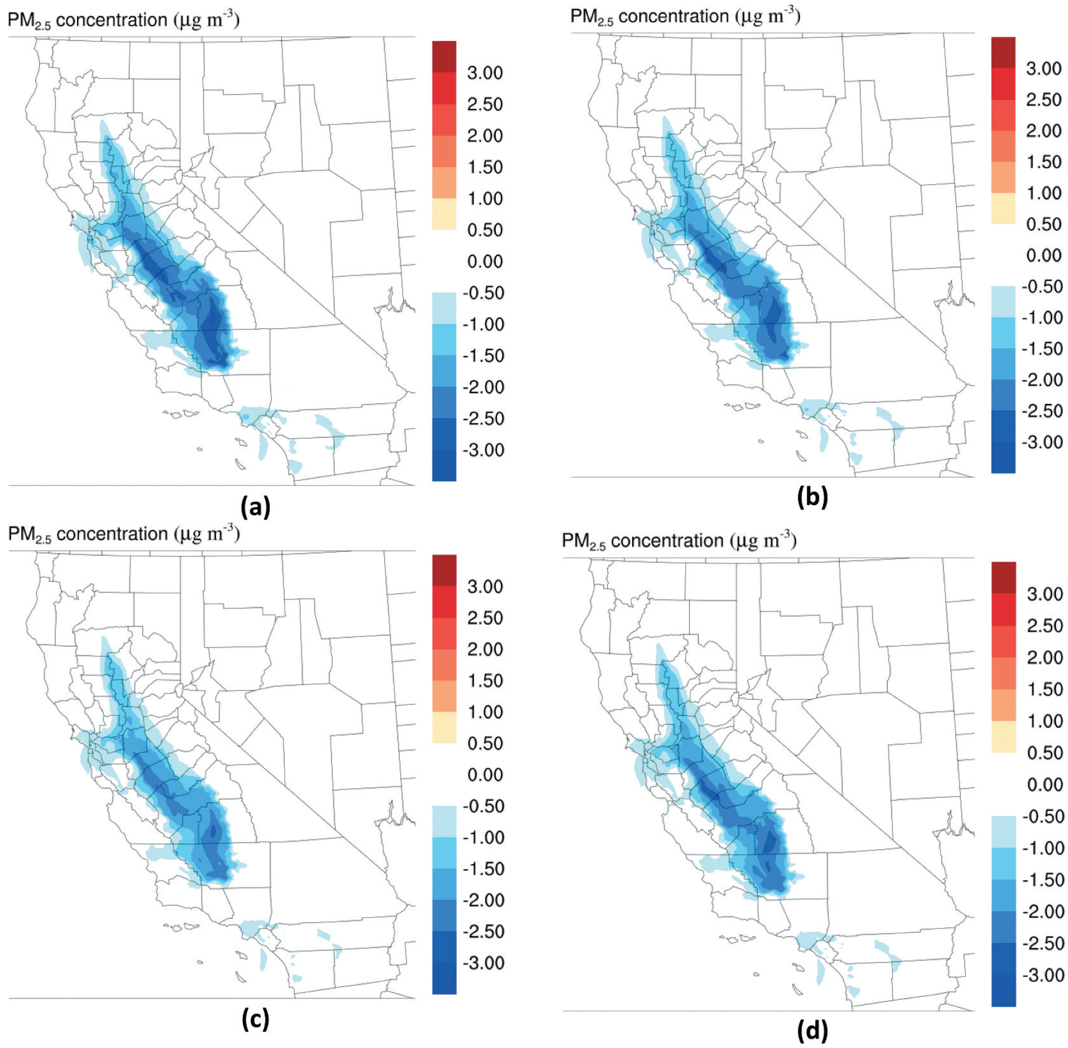

Figure 6. Peak differences in winter episode 24-hr $PM_{2.5}$ between the SIP Case and (a) Case 1B, (b) Case 2A, (c) Case 2C, and (d) Case 2D in ug/m^3.

Table 4. Δ Peak and average ozone and $PM_{2.5}$ concentrations predicted from the SIP case.

	Ground-level Ozone		Ground-level $PM_{2.5}$			
Case	Peak Summer MD8H [ppb]	Average Summer MD8H [ppb]	Peak Summer Max 24-hr [ug/m^3]	Avg. Summer Average 24-hr [ug/m^3]	Peak Winter Max 24-hr [ug/m^3]	Avg. Winter Average 24-hr [ug/m^3]
1B	−6.1	−1.4	−1.2	−0.6	−3.1	−1.8
2A	−5.8	−1.3	−1.1	−0.5	−3.0	−1.7
2C	−5.1	−1.1	−1.0	−0.5	−2.6	−1.5
2D	−5.5	−1.2	−1.0	−0.5	−2.8	−1.6
100 ZEV	−7.6	−3.1	−1.4	−0.7	−3.9	−2.2

they represent a more likely outcome for the California MDV and HVD sectors. However, we also include the valuation for Case 1B relative to the Base Case as this establishes the upper bound for potential health benefits. The mean values estimated for summer are shown in Figure 7 and for winter in Figure 8. For the SIP related cases, health savings in summer are estimated to range from \$47 million to \$56 million as a result of ozone and $PM_{2.5}$ improvements. In winter, health savings for the SIP cases fall between \$36 and \$43 million and result solely from $PM_{2.5}$ reductions. In California, ozone concentrations in winter are often inversely related to emission reductions as a result of titration mechanisms in the atmosphere, and as a result increases are predicted in Southern California which yield a negative value for ozone health savings (shown in Figure SI 12) (Zhu et

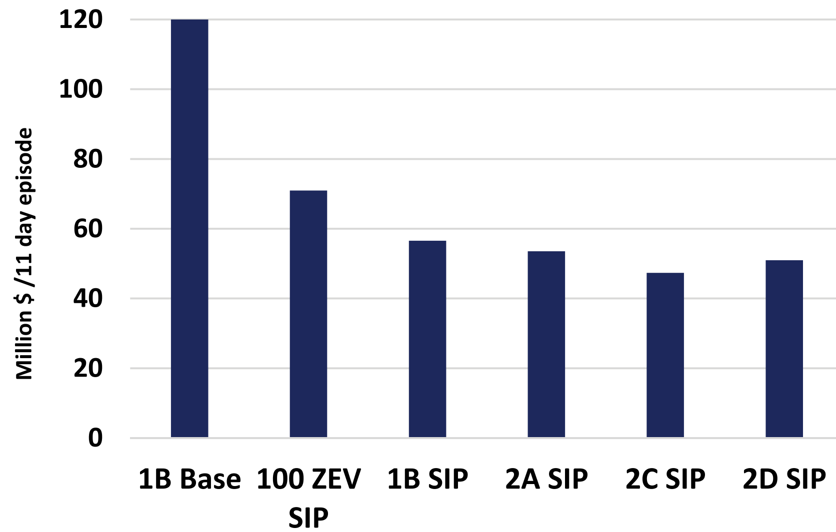

Figure 7. Economic valuation of avoided incidence of mortality and morbidity for the air quality improvements predicted in the summer episode. Values are mean estimates from BenMAP-CE.

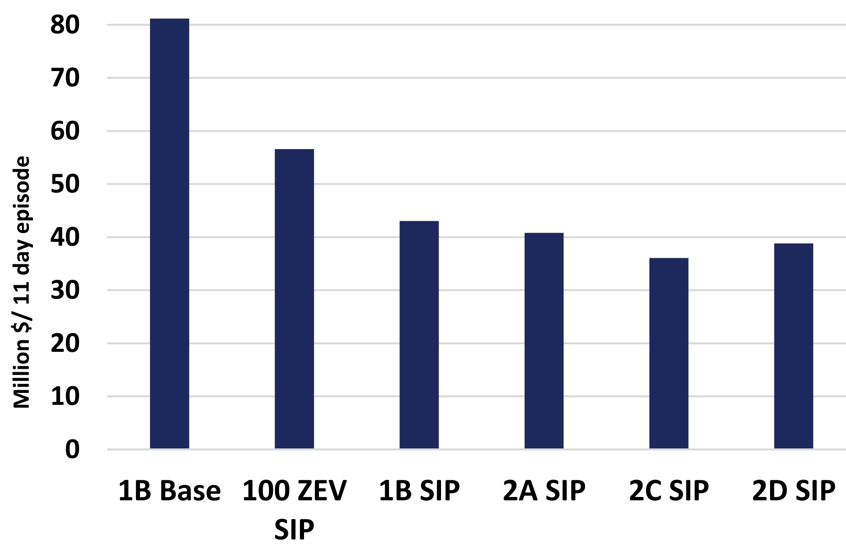

Figure 8. Economic valuation of avoided incidence of mortality and morbidity for the air quality improvements predicted in the winter episode. Values are mean estimates from BenMAP-CE.

al. 2019; Jhun et al. 2015). However, the larger magnitude of health savings from $PM_{2.5}$ ensures an overall benefit is still achieved. Representing the upper bound, health benefits for Case 1B relative to the Base Case could range up to $120 million in summer and $81 million in winter as a result of the greater reductions in pollutant concentrations, as baseline levels are higher in the Base Case compared to the SIP Case. Given the dramatic variation of ozone health impacts between the seasons (i.e., including a sign change), it should be considered that the individual pollutant impacts are more dissimilar than the total health savings may indicate.

The additional health benefits from ZEV can be estimated via comparison with the results for CNG Case 1B relative to the SIP Case, as both assume complete deployment of the relative vehicle type. In the summer, the 100 ZEV achieves an additional $14.4 million, and in the winter an additional $13.5 million. The use of ZEV attains higher health benefits relative to a comparable low-NO_x case due to reductions of all pollutants including PM, ROG, SO_x, and CO, and to a lesser degree the complete elimination of NO_x. The additional emission reductions are particularly important for $PM_{2.5}$ concentrations throughout the state.

Furthermore, it should be considered that chronic exposure to NO_2 (a principal component of NO_x) is associated with deleterious health outcomes including the development of asthma and increased susceptibility to respiratory infections (Chen et al. 2007). While those health benefits are not quantified here, they should be considered as an additional benefit of alternative fuel HDV and MDV that reduce NO_x.

Discussion

The use of low-NO_x CNG engines notably improves AQ from a baseline of vehicles largely comprised of diesel- and gasoline-powered vehicles. These results provide an upper bound for potential AQ benefits as it is expected that future HDV and MDV fleets in California will be comprised of cleaner technologies than those considered in the baseline here, including low-NO_x CNG, battery electric, and hydrogen fuel cell vehicles (Brown 2016). This outcome is more reasonably represented by comparison with the SIP Case, which provides insight into how increasing penetrations of low-NO_x CNG vehicles can impact AQ within the context of a cleaner portfolio of HDV and MDV technologies. However, as noted earlier, the fleet mix in the SIP Case is potentially higher emitting than current regulations would suggest, and the results should be considered as optimistic. The quantified health savings represent important benefits for California and demonstrate the suitability of low-NO_x CNG vehicles within advanced MDV and HDV portfolios seeking AQ improvements. The results from this study further support those from others that have shown public health benefits co-benefits from the use of CNG as a climate mitigation strategy in the HDV sector (Aas et al. 2019; Zhao et al. 2019). We estimate the benefits for replacing only in-state vehicles as potentially exceeding \$50 million for an episode in summer and \$38 million for an episode in winter, demonstrating that shifts to low-NO_x CNG engines are beneficial to AQ even if the challenge of instigating shifts for vehicles outside of California limits deployment.

- Reductions in NO_x provide the largest benefits in ozone and $PM_{2.5}$

While it is expected that NO_x reductions drive overall impacts on ozone, predicted reductions in $PM_{2.5}$ are also primarily influenced by secondary mechanisms associated with emissions of NO_x. This occurs in part as changes in directly emitted $PM_{2.5}$ and ROG are minor compared to the substantial differences in emitted NO_x. Results here demonstrate important seasonal differences in secondary $PM_{2.5}$, with impacts in winter particularly important in the Central Valley with improvements predicted for that period exceeding −1.50 ug/m^3 to −3.41 ug/m^3 depending on the composition of the HDV and MDV fleet. This is a desirable outcome as the Central Valley suffers from winter-time $PM_{2.5}$ levels above health-based standards and the results support similar findings for the region in related studies (Zapata et al. 2018). Impacts on $PM_{2.5}$ for summer conditions are more moderate, and with different spatial occurrence of peak impacts predicted during the winter period, with peak concentration reductions predicted for the SoCAB, and other areas of note including different areas of the Central Valley.

- Air quality benefits often occur in important locations, including disadvantaged communities

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. These areas are often encompass disadvantaged communities as designated by California, further emphasizing the importance of AQ benefits (Faust et al. 2017). Increasing the deployment of low-NO_x 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 deployment of low-NO_x 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.

- Trade-offs between low-NO_x CNG and ZEV should be considered in the design of policy promoting cleaner MDV and HDV fleets

The current commercial readiness of low-NO_x CNG engines, in contrast to the prominent zero-emission options of battery electric and hydrogen fuel cell, allows the opportunity for near- and mid-term emission reductions that could be particularly significant in regions of non-compliance (Couch et al. 2019). For example, the foremost AQ challenge facing SoCAB is the reduction of NO_x sufficient to comply with ozone standard deadlines in 2031 (Shen, Oliver, and Dabirian 2017). Within this timeline, low-NO_x CNG could be an important solution in the MDV and HDV sectors and offer considerable AQ benefits within disadvantaged communities. However, zero-emission options, including battery electric and hydrogen fuel cell trucks, attain higher health benefits than low-NO_x CNG vehicles and represent the ultimate answer for sustainable trucking, and it is unknown if large-scale shifts to CNG could delay or prevent commercialization progress in California for those options, e.g., average vehicle lifetimes could result in CNG engines remaining in fleets for a decade or more. Here, we estimate that the health savings attainable from ZEV could be up to 25% higher in summer and 31% higher in winter than those from low-NO_x CNG for equivalent vehicle deployment levels. Tradeoffs should be considered within the context of policy seeking emission reductions and AQ benefits from the on-road sector. These tradeoffs must also be considered from a climate policy perspective, as the selection of vehicle technology and fuel combinations will determine GHG footprints from fleets. A short-term promotion of CNG use could delay or prevent more optimal integrated solutions in the mid-term, for example. In addition, work characterizing the techno-economics of transitions to fuel supply chains for the production, distribution, and dispensing of low carbon NG fuels, including renewable natural gas (RNG), should also be considered within this context as they would be necessary to ensure GHG reductions (Lane 2019).

It has also been shown that in-use NO_x emissions from current diesel vehicles exceed certification standards as a result of poor aftertreatment system performance during low duty cycle operation (Miller et al. 2013). Similar work has verified the NO_x reduction of low-NO_x CNG engines to be independent of duty cycle (Johnson 2018). Therefore, results here could be underestimated as emission reductions are estimated assuming diesel vehicles are maintaining satisfactory compliance with emission regulations. Conversely, it has also been shown that emitted particles, ammonia, and methane were higher than diesel engines on similar drive cycles (Johnson 2018). This was not represented in the modeling conducted for this work, and should be considered in future work due to important AQ and GHG implications, particularly given the importance of ammonia emissions to $PM_{2.5}$ formation and associated health impacts (Watson and Chow 2002).

- Chemical differences in PM occurring from fuel composition differences between gasoline and diesel vehicles and CNG vehicles may yield additional public health impacts for CNG vehicles

Direct PM emissions are assumed to be reduced moderately for low-NO_x CNG engines relative to advanced diesel and gasoline engines in terms of total mass. However, the chemical composition of emitted PM is also likely to be substantially different due to differences in fuel composition and other combustion parameters (Kakaee, Paykani, and Ghajar 2014). The chemical composition of PM is a direct determinant of human health impacts, and thus exposure to $PM_{2.5}$ generated from low-NO_x CNG engines may have dissimilar health impacts compared to exposure to diesel or gasoline generated $PM_{2.5}$. This is an issue that would benefit from further study including focused toxicological research with similarity to studies done for exposure to first-generation biodiesel fuels (Gookin 2011; Valand et al. 2018).

It should also be considered that shifts in the NO_2/NO_x ratio could occur from transitions to CNG vehicles. This phenomenon has been observed in Europe, potentially as a result of emission control technologies and shifts in vehicles and fuels (Carslaw 2005). In addition to direct health implications from NO_2, changes in the ratio could affect formation mechanisms associated with ozone.

Conclusion

The results demonstrate the substantial public health savings from AQ improvements that deploying alternative vehicle and fuel platforms in the medium- and heavy-duty sectors can attain, particularly within socially vulnerable communities. Improvements to $PM_{2.5}$ in winter in the Central Valley and ozone in summer in Southern California are pronounced. The extent of these benefits depends on the selection of vehicle and fuel combinations and the timing of fleet penetration. Policy development should weigh the potentially higher near-term benefits from CNG resulting from enhanced commercialization against the higher longer-term benefits from zero-emission options.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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