Literature Review of Ammonia Emissions from On- and Off-Road Mobile Sources

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1. Introduction, Summary, and Document Organization

1.1 Introduction

Emissions standards for on- and off-road mobile sources have become increasingly stringent to protect human health and the environment. In the United States, these emission standards focus on nitrogen oxides (NO_x), volatile organic compounds (VOCs), and fine particulate matter ($PM_{2.5}$). Selective catalytic reduction (SCR) systems that reduce emissions of NO_x from diesel engines also produce emissions of ammonia (NH_3). Three-way catalytic converters used to reduce NO_x emissions from gasoline engines also produce NH_3. These emissions of NH_3 are an unwanted byproduct from the NO_x-control technologies. NH_3 is a gaseous precursor to the secondary formation of $PM_{2.5}$ through chemical reactions with NO_x and sulfur oxides (SO_x). Since $PM_{2.5}$ is a regulated criteria air pollutant under the National Ambient Air Quality Standards (NAAQS), there is growing concern about NH_3 emissions from mobile sources due to its role in $PM_{2.5}$ formation and the health risks associated with $PM_{2.5}$ concentrations.

This technical memorandum summarizes the results of a literature review focused on NH_3 emissions from on- and off-road mobile sources, as well as the associated ambient air concentrations of NH_3, air quality and climate impacts, and health risks. The literature review was conducted to help Caltrans understand (1) the extent to which the use of certain technologies for controlling exhaust emissions of NO_x from on- and off-road mobile source engines result in exhaust emissions of NH_3; and (2) potential adverse impacts of project specifications that introduce or require fuel and/or equipment to meet the requirements of the California Low Carbon Fuel Standard (LCFS) regulation.

1.2 Summary

What is NH_3 and Why is it Important?

NH_3 is a gas-phase pollutant that is emitted into the atmosphere through natural and anthropogenic (human-caused) emissions sources, including motor vehicles and off-road construction equipment. NH_3 is toxic to humans at high concentrations, but ambient concentrations of NH_3 (annual average of 0.5 to 20 µg/m^3, or 0.75 to 30 ppb) do not produce adverse health effects and are well below the Chronic Reference Exposure Level (200 µg/m^3, or 300 ppb) set by the California Office of Environmental Health Hazard Assessment (OEHHA). Atmospheric concentrations of NH_3 are still important to consider for air quality, visibility, and human health because NH_3 contributes to the secondary formation of $PM_{2.5}$ through chemical reactions with NO_x and SO_x. NH_3 from deposition to the ground surface can also affect the quality of the environment through acidification and eutrophication of natural ecosystems.

Are NH_3 Emissions From Mobile Sources Regulated?

NH_3 emissions from mobile sources are not currently regulated in the United States, but they are regulated in Europe. Regulations to address $PM_{2.5}$ pollution in California have largely focused on reducing primary sources of $PM_{2.5}$ pollution, such as agricultural burning and residential wood combustion and reducing NO_x emissions from the transportation sector. Although NH_3 is not a criteria pollutant for the NAAQS, the U.S. Environmental Protection Agency (EPA), California Air Resources Board (CARB), and local air districts could potentially regulate NH_3 emissions to address $PM_{2.5}$ NAAQS nonattainment.

How do NH_3 Emissions Arise From Motor Vehicles?

NH_3 is emitted as an unwanted byproduct from the control technology used to reduce NO_x emissions. In diesel vehicles equipped with SCR systems, this is commonly referred to as “NH_3 slip.” NH_3 is also produced by gasoline vehicles equipped with three-way catalytic converters. Since NH_3 is not a regulated pollutant, publicly available data on NH_3 emissions from motor vehicles are somewhat limited, but there has been increased focused on understanding and quantifying NH_3 emissions from mobile sources. There are only a limited number of scientific studies on NH_3 slip and NH_3 emissions from off-road diesel equipment.

How Much NH_3 do Mobile Sources Emit?

On a statewide basis, agriculture and livestock are the dominant sources of anthropogenic NH_3 emissions. NH_3 emissions from the transportation sector are comparatively small but are non-negligible, and there are multiple and somewhat conflicting estimates of these NH_3 emissions. According to EPA’s National Emissions Inventory (NEI), on-road motor vehicles in California emitted 10,069 tons/year of NH_3 in

2020, or 2.2% of total statewide NH_3 emissions, whereas CARB's EMFAC2021 model for California's on-road mobile source emissions estimated 15,313 tons/year of NH_3 emissions from on-road vehicles in 2020. The California Emissions Projection Analysis Model (CEPAM) indicates that on-road mobile sources account for up to 8% of statewide NH_3 emissions in 2020. In EMFAC2021, NH_3 emissions from mobile sources are projected to increase in future years, but the rate of increase for on-road vehicles is less pronounced beyond 2030 due to increased fleet turnover toward zero-emission vehicle technology. Based on currently available data, off-road equipment represents about 1% of statewide NH_3 emissions from mobile sources, and this value is much less than 1% when considering construction equipment commonly used for Caltrans roadway construction projects.

In contrast to the statewide inventories, recent studies have observed that mobile source NH_3 emissions may be significantly underestimated, perhaps by a factor of 2-5 or more, and mobile sources may contribute 30-50% of total NH_3 emissions in large urban areas that have limited sources of agriculture or livestock emissions. On-road NH_3 emissions in these urban areas are co-emitted with NO_x, providing a potentially effective pathway to secondary $PM_{2.5}$ formation.

There has been increased attention on NH_3 emissions from mobile sources in recent years. For example, CARB added NH_3 emissions to EMFAC2021, and EPA recently made a significant update to some of the NH_3 emission factors in the latest version of their on-road mobile sources emissions model (the MOtor Vehicle Emissions Simulator [MOVES]) to account for recent emissions measurement data. The updated NH_3 emission factors in MOVES will significantly increase the estimated nationwide NH_3 emissions from mobile sources, especially for historical and near-term years, and ongoing chemical transport modeling by EPA suggests this may have a non-negligible impact on urban $PM_{2.5}$ concentrations.

Can NH_3 Emissions From Motor Vehicles be Controlled?

In an SCR system, increasing the NO_x conversion rate can lead to increased NH_3 slip. NH_3 emissions can be reduced with after-treatment devices such as NH_3 slip catalysts (ASC) or NH_3 oxidation catalysts (AMOX) that oxidize unreacted NH_3 downstream of the NO_x emission control system. At this time, there is no requirement for NH_3 control devices to be installed on diesel trucks or construction equipment in the United States, as current U.S. motor vehicle emission standards do not address NH_3 emissions. However, in Europe, the heavy-duty Euro IV emission standards include a 10 ppm cycle-average slip limit for tailpipe NH_3 emissions, and more stringent limits on tailpipe NH_3 emissions have been proposed for the future Euro 7 regulations.

Implications and Recommendations for Caltrans

There are several implications and recommendations for Caltrans based on this literature review.

- Emissions of NH_3 from mobile sources are increasing due to increased travel activity and the increased use of SCR systems to control NO_x emissions from diesel vehicles. Gasoline vehicles with three-way catalytic converters also produce NH_3 emissions.
- Although the contribution of NH_3 emissions from mobile sources is clearly increasing, current inventories suggest these emissions are relatively small (2-8% of statewide NH_3 emissions) compared to other major sources of NH_3 such as agriculture and livestock. The contribution from off-road equipment is even smaller (about 1% of statewide mobile source NH_3 emissions), and the contribution from Caltrans construction equipment (as defined in the Caltrans Construction Emissions Tool [CAL-CET]) is smaller still (much less than 1% of statewide mobile source NH_3 emissions).
- The magnitude of NH_3 emissions from mobile sources may be larger than previously thought, and therefore there is increased attention on estimating and understanding NH_3 emissions from mobile sources.
- The substantial NO_x and $PM_{2.5}$ emission reductions achieved by Tier 4 construction equipment (compared to older construction equipment) likely far outweigh the increased NH_3 emissions produced by SCR control equipment.
- In diesel vehicles with an SCR system, there is a tradeoff between the reduction of NO_x emissions and the NH_3 emissions produced via NH_3 slip. This tradeoff would be an important consideration if mobile source NH_3 reductions are contemplated in the future. Stringent reduction of both NO_x and NH_3 emissions could require installation of after-treatment devices on vehicles to remove NH_3 from the exhaust stream. Such control technology exists but is not currently required.
- Caltrans should continue to monitor ongoing work to improve and update NH_3 emission factors in EMFAC and MOVES. Recent updates in MOVES4 substantially increased the estimated NH_3 emissions from that model, and in the future these changes will be reflected in national emission inventories.
- Caltrans should continue to monitor the scientific literature for studies that focus on NH_3 emission factors, the development of improved on-road NH_3 emission inventories, and estimation of the contribution of traffic sources to total NH_3 emissions in different areas.

1.3. Document Organization

This document provides information developed from the literature review of NH_3 emissions from on-road and off-road mobile sources. The document is organized as follows:

- **Section 1** (this section) provides an introduction, a summary of key findings and implications from the literature review, and an outline of the document organization.
- **Section 2** provides background information.
- **Section 3** presents the search strategy used for the literature review and provides an overview of the relevant literature found.
- **Section 4** describes relevant studies and available data on NH_3 emissions from on- and off-road mobile sources and options for controlling those emissions.
- **Section 5** provides a brief discussion of the air quality and climate impacts associated with NH_3 emissions.
- **Section 6** describes the health risks associated with NH_3 emissions.
- **Section 7** provides a conclusion and recommendations for further consideration.
- **Appendix A** provides a summary of the literature that was considered in this review.

2. Background

NH_3 and its Importance

Emissions standards for on- and off-road mobile sources have become increasingly stringent in order to protect human health and the environment. Common methods to control emissions of NO_x from diesel-powered mobile source engines include SCR and selective non-catalytic reduction (SNCR) systems. These technologies inject NH_3 or urea, which are used as reducing agents, into the post-combustion gases, and typically have an associated "slip" of unreacted NH_3 from the control system into the exhaust emissions.

NH_3 is a gaseous precursor to the formation of $PM_{2.5}$ through chemical reactions with NO_x and SO_x. Since $PM_{2.5}$ is a regulated criteria air pollutant under the NAAQS, there is growing concern about NH_3 emissions from mobile sources due its role in secondary formation of $PM_{2.5}$ and the health risks associated with $PM_{2.5}$ concentrations. As a result, NH_3 emissions from on-road vehicles and off-road construction equipment associated with Caltrans transportation projects may become an increasingly important factor for project planning and air quality considerations.

Contribution of Mobile Sources to NH_3 Emissions

Recent scientific literature suggests that the contribution of on- and off-road mobile sources to NH_3 emissions in urban areas has been growing. This has important implications for assessing and mitigating air quality, climate, and health impacts from NH_3 emissions. When vehicles use SCR systems, there is a tradeoff between desired NO_x emission reductions and unwanted NH_3 emissions produced by NH_3 slip. SCR systems are necessary in order to meet Tier 4 NO_x emissions standards for off-road diesel equipment. The resulting increase in NH_3 emissions associated with Tier 4 equipment should be viewed in the context of the substantial reductions in NO_x (and $PM_{2.5}$) emissions that are achieved through the use of Tier 4 engines.

On a statewide basis, agriculture, livestock, and waste disposal are the dominant sources of NH_3 emissions in California. However, recent literature suggests that mobile source NH_3 emissions may be significantly underestimated in current emission inventories, perhaps by a factor of 2-5 or more, and that mobile sources may actually be a significant source of NH_3 emissions in large urban areas.

Ambient NH_3 Concentrations and Health Benchmarks

EPA operates the Ammonia Monitoring Network (AMoN), which measures ambient NH_3 concentrations and the deposition of reduced nitrogen species at more than 100 rural sites across the United States. In 2017, the annual average atmospheric concentrations of NH_3 observed at AMoN sites ranged from 0.5 to 20 $\mu g/m^3$ (0.75 to 30 ppb).[1] These ambient concentrations do not produce adverse health effects and are well below all known health-based concentration thresholds for NH_3. The EPA set a Chronic Reference Concentration (RfC) of 0.5 mg/m^3 (500 $\mu g/m^3$) for NH_3 in the 2016 Integrated Risk Information System (IRIS) (EPA, 2016).[2] The RfC is the estimated concentration level where, when inhaled continuously by humans, would likely cause no risks of deleterious effects during a lifetime. Additional agencies have set health-based guidelines ranging from 0.2–35 mg/m^3 (0.3–50 ppm, or 300 to 50,000 ppb) across different averaging times (OEHHA, 1999; U.S. Center for Disease Control, 2019; Nielsen et al., 2007).

Controlling NH_3 Emissions from Mobile Sources

Options for reducing NH_3 emissions depend on the dominant sources of NH_3, the composition of other emissions and pollutants in an area of interest, as well as the feasibility of implementing effective strategies. Some emission sources may not be readily or reasonably controlled and regulated. The composition of atmospheric

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[1] See the **AMoN fact sheet** (https://nadp.slh.wisc.edu/wp-content/uploads/2020/11/AMoNsheet.pdf).
[2] All cited references in this document are listed in Appendix A.

pollution in an area, including $PM_{2.5}$ and its gaseous precursors, will depend on the source contributions and local-to-regional meteorological conditions, and the composition will influence the potential effectiveness of various control strategies for NH_3 emissions. In areas with large sources of NH_3 emissions (e.g., concentrated animal feeding [CAF] sites, agricultural areas, and waste disposal facilities), formation of $PM_{2.5}$ may be "NO_x-limited" due to the abundance of available NH_3, and therefore $PM_{2.5}$ formation would be relatively insensitive to changes in NH_3 emissions. In urban areas where NH_3 is co-emitted with NO_x, options for controlling NH_3 slip emissions from on- and off-road mobile sources (such as ASC or AMOX devices mentioned in **Section 1.2**) could potentially be more effective than controlling NH_3 emissions from the major, typically non-urban sources of NH_3 (e.g., agriculture and CAF sites) that may contribute to NH_3 concentrations in downwind urban areas.

Historically, achieving NAAQS attainment for $PM_{2.5}$ in California has been addressed by controlling primary $PM_{2.5}$ emissions and precursor NO_x emissions, rather than by controlling precursor NH_3 emissions. Recent modeling conducted by the California Air Resources Board (CARB) and the San Joaquin Valley Air Pollution Control District (SJVAPCD) (CARB, 2023) suggests that reasonable NH_3 control options for CAF, agricultural, and waste disposal sources in the San Joaquin Valley would produce only a small reduction in $PM_{2.5}$ concentrations, and therefore NH_3 control strategies from these sources would not be effective. In urban areas with lower levels of NH_3 emission sources from agriculture and livestock, $PM_{2.5}$ concentrations may be more sensitive to reductions of NH_3 from on- and off-road mobile sources achieved through use of ASC or AMOX after-treatment devices. Although NH_3 emissions from mobile sources may currently be underestimated in emissions inventories, they comprise 2-8% of total statewide NH_3 emissions based on current inventory estimates.

3. Literature Search Strategy and References Summary

Literature searches for information and data on NH_3 emissions from on- and off-road mobile sources, control technologies for those NH_3 emissions, and related air quality, climate, and health impacts were conducted via the internet using eleven combinations of keywords in Google Scholar and two dozen combinations of keywords in Google, as listed in **Tables 1 and 2**. The relevant references that were reviewed or considered are listed in **Appendix A**, which also indicates the topic areas considered in this literature review that each reference addressed.

Because NH_3 emissions from mobile sources are not regulated, publicly available data on NH_3 emissions from these sources are somewhat limited. The review documented here found that the literature on NH_3 slip emissions from mobile sources is heavily focused on on-road vehicles as opposed to off-road equipment. Emission inventories for California from EPA and CARB were considered as part of this literature review to supplement the limited number of studies or documentation on NH_3 emissions from off-road equipment.

Table 1. List of keyword combinations used for Google Scholar searches.

Table Summary: This table lists the keyword combinations used in Google Scholar searches for literature on NH_3 emissions and concentrations, and the associated impacts on air quality and climate, and health risks.

ID	Keyword Combinations in Google Scholar Searches
1	ammonia construction equipment
2	atmospheric ammonia diurnal patterns
3	construction ammonia emissions
4	construction equipment ammonia emissions
5	heavy duty ammonia emissions
6	lawn equipment ammonia emissions
7	mobile equipment ammonia emissions
8	mobile source ammonia air concentrations
9	non-road mobile machinery NRMM
10	off-road emissions ammonia
11	road emissions ammonia

Table 2. List of keyword combinations used for Google searches.

Table Summary: This table lists the keyword combinations used in Google searches for literature on NH_3 emissions and concentrations, and the associated impacts on air quality and climate, and health risks.

ID	Keyword Combinations in Google Searches
1	"AMOX" ammonia oxidation catalyst
2	ammonia construction equipment
3	ammonia construction equipment heavy duty
4	ammonia emissions from tier 4 off-road equipment engines
5	"ammonia emissions" renewable diesel equipment
6	California air emissions ammonia
7	CARB ammonia emissions standards
8	CARB ammonia emissions standards California
9	CARB California emission inventory “ammonia"
10	CARB California emission inventory "ammonia" toxic
11	CARB emission inventory ammonia
12	CARB mobile source ammonia
13	CARB off-road emissions inventory
14	EPA air trends pm2.5 composition nation
15	EPA ammonia mobile
16	EPA ammonia off-road
17	EPA ammonia slip emissions limit
18	european environmental agency mobile source ammonia
19	OFFROAD 2011 emissions inventory California
20	south coast aqmd ammonia exhaust
21	south coast aqmd ammonia vehicle emissions
22	us EPA mobile emissions ammonia
23	us air emissions ammonia

4. NH_3 Emissions from Mobile Sources

4.1 Overview

On the national scale, it has been widely considered that mobile sources contribute only a small portion of total NH_3 emissions, with agricultural sources being the dominant source. **Figure 1** presents NH_3 emissions from the 2020 NEI across different sectors. The NEI uses sector-specific methodologies to estimate NH_3 emissions. For example, NH_3 emissions from agricultural sources are estimated using a modeling approach that accounts for land use, agricultural activity (e.g., crop type and fertilizer application), meteorology, and bidirectional NH_3 exchange between the air and surface, while NH_3 from mobile sources are estimated using EMFAC (for California) or EPA's MOVES3 model.[3] The NEI data shows an overall decline in NH_3 emissions from the "Transportation" sector (including on-road vehicles and off-road equipment) in the last 20 years, from ~4% to ~2% of total NH_3 emissions. **Table 3** summarizes the 2020 NEI data for only California in calendar year 2020. The table shows that on-road vehicles account for ~2% of total NH_3 emissions in California, while off-road equipment account for << 1%. These are statewide totals and do not reflect contributions of mobile sources to NH_3 emissions in urban areas alone.

[3] Updates to NH_3 emission rates for on-road vehicles in the latest version of MOVES (MOVES4) include increases ranging from about 40% to a factor of four, depending on vehicle type (light-duty or heavy-duty), model year, and fuel type. In MOVES4, total on-road NH_3 emissions are dominated by the contribution from light-duty vehicles (e.g., in calendar year 2023, light-duty gasoline vehicles account for 84% of the inventory, while heavy-duty diesel vehicles account for 12%); and light-duty vehicles are expected to be the major on-road source in urban areas. See data presented in **Planned Updates to Ammonia (NH_3) and Nitrous Oxide (N_2O) in MOVES4** (https://www.epa.gov/system/files/documents/2023-08/moves4-plan-update-nh3-n2o-webinar-2023-07-20.pdf).

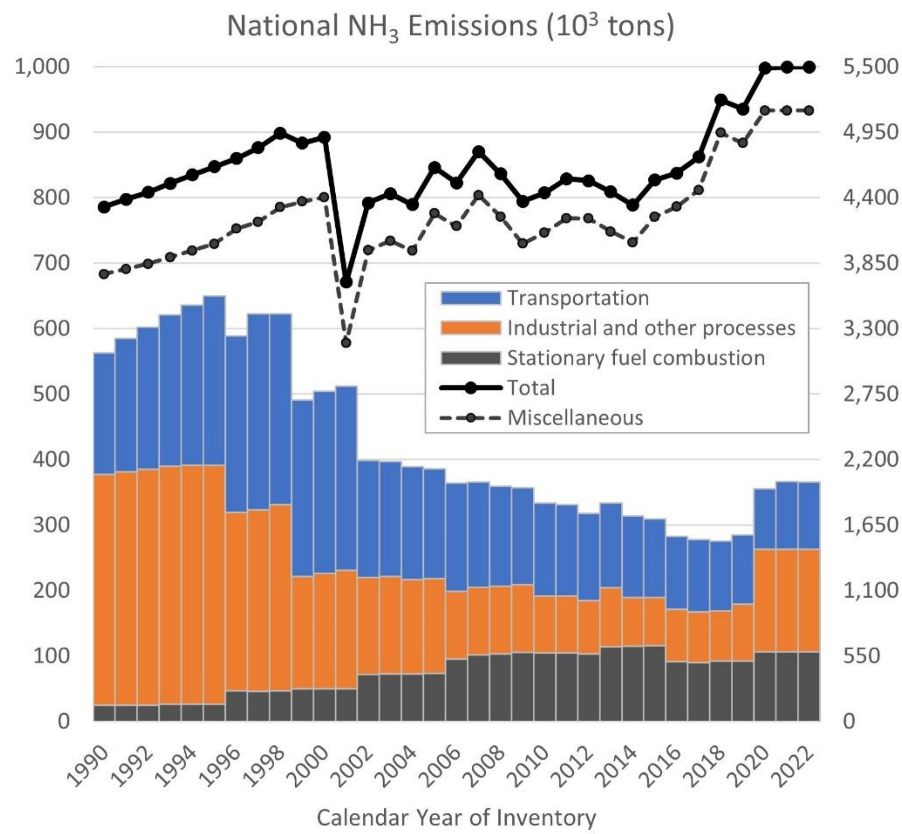

Figure 1. NH_3 emissions (in 10^3 tons) from different sources in the 2020 NEI.

Table 3. NH_3 emissions by source category in California for calendar year 2020 (2020 NEI).

Table Summary: This table summarizes the levels of NH_3 emissions for calendar year 2020 from different sources categories in the 2020 NEI and the percentage of the total that each source category contributes. The on-road vehicle and off-road equipment/vehicle mobile sources are indicated in the table with **bold black** font.

Source Category	NH_3 Emissions (tons)	% of Total NH_3 Emissions
Agriculture	315,421	70%
Fires	111,421	25%
On-road light-duty vehicles (LDVs)	**9,364**	**2%**
Stationary fuel combustion	6,657	1%
Waste Disposal	5,834	1%
On-road heavy-duty vehicles (HDVs)	**705**	**< 1%**
Off-road equipment/vehicles	**137**	**≪ 1%**
Commercial marine vessels & locomotive	21	≪ 1%
Pleasure craft and rail equipment	15	≪ 1%
Total	**449,575**	**100%**

Compared to the 2020 NEI, the California inventory based on CEPAM2019 v1.03[4] (noted in the Introduction) estimates a larger contribution from on-road vehicles in the state (~8% vs. ~2% of total NH_3 emissions), and the CARB mobile source emission inventory models yield greater NH_3 emissions in the state (15.5×10^3 tons/year) compared to the NEI (10.2×10^3 tons/year).

Table 4 and **Figure 2** summarize results from the latest CARB on-road and off-road mobile source inventories, EMFAC2021 v1.0.2 and OFFROAD2021 v1.0.5, for all applicable on-road vehicle classes and selected off-road equipment types for calendar years 2020, 2030, 2040, and 2050. These inventory data indicate that all off-road equipment produces about 1% of the amount of NH_3 emissions produced by on-road vehicles statewide. That value drops to << 1% when considering only off-road equipment types that are commonly used for Caltrans construction projects, i.e., those equipment types included in the Caltrans Construction Emissions Tool (CAL-CET2021 v1.0.2) based on historical Caltrans construction project diary data. The NH_3 emissions from both on-road and off-road sources are projected to increase in future years due to

[4] CEPAM forecasts future-year emissions using current growth and control data. For mobile sources, CEPAM integrates emissions estimates from the EMFAC and OFFROAD models. CARB uses CEPAM to develop future-year emission inventories to support SIP attainment modeling and progress tracking.

increased travel activity and increased penetration of SCR systems in diesel engines. The rate of increase for on-road vehicles is less pronounced beyond 2030 due to increased fleet turnover toward zero-emission vehicle technology.

Table 4. NH_3 emissions (in tons) from mobile sources in CARB emission inventories.

Table Summary: This table summarizes the levels of NH_3 emissions from mobile sources in California in the CARB emission inventories for on-road vehicles and off-road equipment. The table includes total NH_3 emissions from all on-road vehicle classes and selected off-road equipment types from the CARB EMFAC2021 v1.0.2 and OFFROAD2021 v1.0.4 emission inventories for the calendar years 2020, 2030, 2040, and 2050.

Mobile Source Category and Vehicle/Equipment Types	2020	2030	2040	2050
On-road vehicles (EMFAC2021 v1.0.2 – all vehicles/fuel types)	15,313	21,574	22,665	23,869
All off-road equipment (OFFROAD2021 v1.0.5 – all equipment and fuel types)	201	237	266	322
Off-road equipment (OFFROAD2021 v1.0.5 – construction, industrial, and light commercial equipment types in CAL-CET2021 v1.0.2)	17	21	22	24
Off-road equipment (OFFROAD2021 v1.0.5 – diesel construction, industrial, and light commercial equipment types in CAL-CET2021 v1.0.2)	1.2	1.3	1.3	1.3

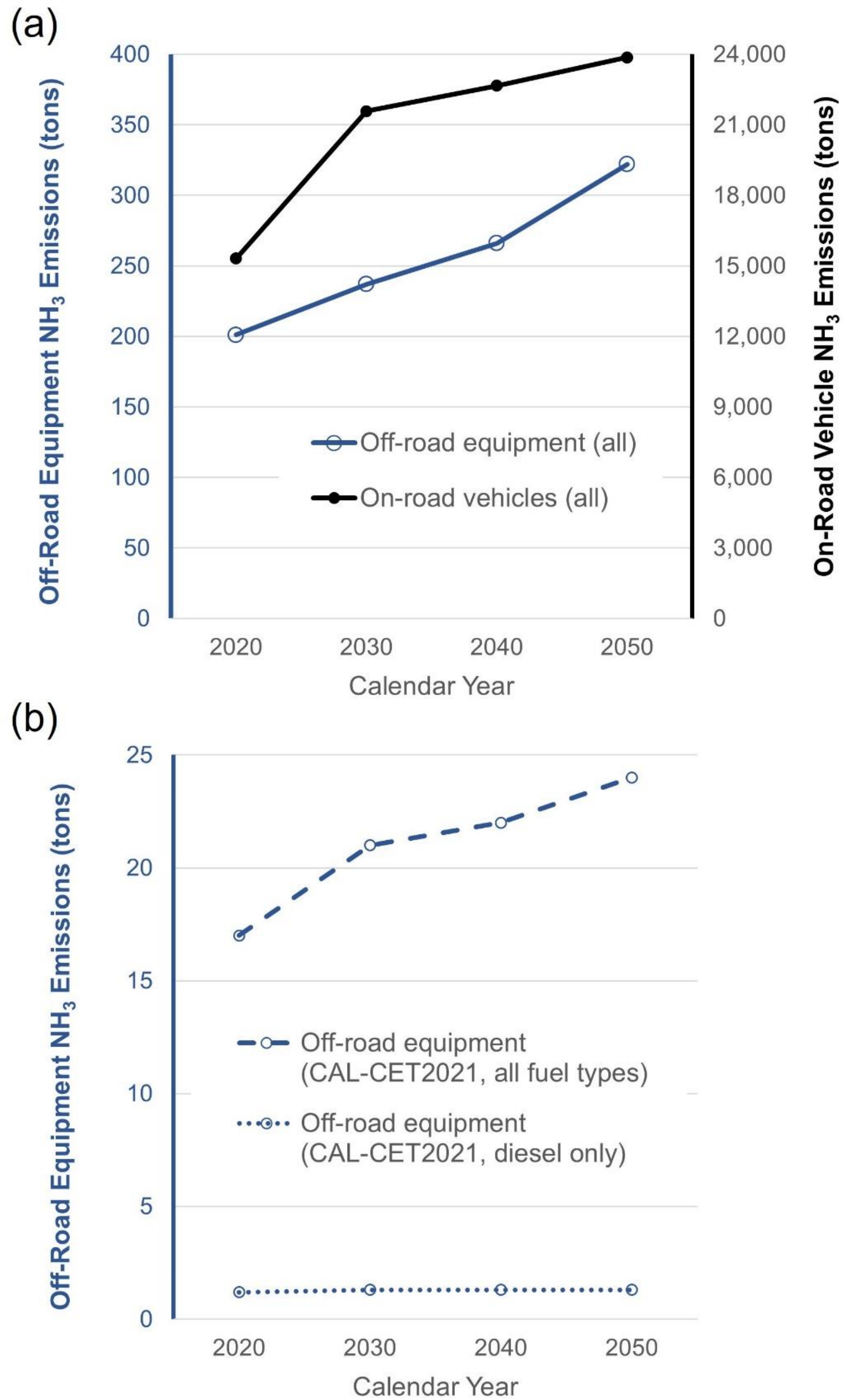

Figure 2. NH_3 emissions from off-road equipment and on-road vehicles in CARB emission inventories: (a) all off-road equipment types and on-road vehicles in the CARB inventories; (b) only off-road equipment included in CAL-CET2021, covering all fuel types in the CARB inventory and only diesel-fueled equipment.

In contrast to the national and state-developed emission inventories, recent studies have observed that vehicle NH_3 emissions in urban areas may contribute 30–50% of total NH_3 emissions (Fu et al., 2005; Roe, 2004; Whitehead et al., 2007; Meng, 2011; Bishop and Stedman, 2015; Cao et al., 2022). Some studies suggest nearly half of the U.S. population may live in locations where on-road NH_3 emissions exceed agricultural emissions (Fenn et al., 2018; Sun et al., 2017). Using the unique traffic activity impacts of the COVID-19 pandemic lockdown in the spring of 2020, Cao et al. (2022) found that NH_3 emissions from on-road vehicles account for 46% (bottom-up estimate) and 60–95% (top-down estimates) of total NH_3 emissions in Western Los Angeles, corresponding to a factor of ~2–5 underestimation of the on-road vehicle contribution. Farren et al. (2020) found that NH_3 emissions from passenger cars in the United Kingdom are underestimated by a factor of 15. Additionally, mobile sources often co-emit NH_3 with NO_x and SO_x, and although NH_3 (a chemical base) can neutralize those acidic species, the reaction can lead to enhanced $PM_{2.5}$ formation (Seinfeld, 2004).

4.2 NH_3 Slip

NH_3 emissions from on- and off-road mobile sources are not a direct product of the fuel combustion process, but a byproduct of exhaust treatment known as "NH_3 slip." Exhaust treatment systems, which include three-way catalytic converters (TWC) in spark-ignition (such as gasoline) vehicles and SCR and SNCR systems in diesel engines, have greatly improved the ability to remove unburned pollutants, including hydrocarbons (HCs), carbon monoxide (CO), and NO_x, from the engine exhaust stream. NO_x is reduced in the exhaust stream to nitrogen and water using a reductant and a catalyst in SCR systems. In spark-ignition engines, NO_x-reducing agents are naturally present in the combustion exhaust gas (e.g., CO, H_2, and HC); and in diesel systems with SCR or SNCR systems, the reductant, usually NH_3 or urea, is added to the exhaust gas. Unreacted NH_3 in the NO_x-reduction process is emitted in the exhaust stream if not otherwise controlled. NH_3 emissions can be reduced with after-treatment devices such as a ASC or AMOX catalyst that oxidizes unreacted NH_3 downstream of the SCR or SNCR system, but at this time there is no regulatory requirement for these devises to be installed as standard equipment for mobile engines.

The Clean Air Act provides federal authority for regulating NH_3 emissions, but the EPA does not currently regulate NH_3 emissions from mobile sources. Since NH_3 is a precursor to forming $PM_{2.5}$, NH_3 emissions could potentially be regulated in the future to address $PM_{2.5}$ NAAQS nonattainment. It is worth noting that motor vehicle NH_3 emissions are regulated in Europe. The Stage IV emissions standards in the European Union (EU) require that NH_3 slip emissions not exceed 10 ppm (ICCT, 2016), and more stringent limits on tailpipe NH_3 emissions have been proposed for the future Euro 7 regulations.[5]

In general, higher NH_3 slip is associated with cold starts, aggressive acceleration, or high engine load. The amount of NH_3 emitted from vehicles will depend on additional factors such as vehicle type, vehicle age and condition, fuel type, and driving conditions as described below:

- **Vehicle type**
  - Emissions have been observed to be moderately correlated with engine size and the number of cylinders, where NH_3 slip increases with increasing engine size and number of cylinders (Abualqumboz et al., 2022).
- **Vehicle age**
  - Emissions have been observed to increase as vehicle mileage increases, and were highest in the odometer mid-range (~100,000 miles) (Livingston et al., 2009).
  - Bishop and Stedman (2015) noted lower NH_3 emissions among the newest light-duty (gasoline) vehicles compared to a growing number of older vehicles with active catalytic converters; e.g., the authors measured modest NH_3 emission reductions (0–28% reduction, depending on geographic location) between the years 2005 and 2013 in three urban locations. During this time period, new vehicle NH_3 emissions appear to be declining but the number of vehicles in the fleet capable of producing NH_3 has increased.
  - Emissions testing of light-duty gasoline vehicles by Abualqumboz et al. (2022) showed that older motor vehicles with high odometer readings had higher NH_3 emission rates compared to newer vehicles with low odometer readings.
- **Fuel type**
  - NH_3 emissions are expected to vary across fuel types:
    - Diesel-fueled light-duty vehicles have been observed to have lower emissions than gasoline-fueled light-duty vehicles (Abualqumboz et al., 2022; Farren et al., 2020).

[5] European Commission, Directorate-General for Internal Market, I., Entrepreneurship, and SMEs: Technical studies for the development of Euro 7 : testing, pollutants and emission limits, Publications Office of the European Union, doi/10.2873/97170, 2022.

    - Biodiesel has been observed to have lower emissions than low sulfur diesel and ultra-low sulfur diesel (Borillo et al. 2015).
    - Compressed natural gas (CNG) was observed to have emissions ~10 times higher than diesel in light-duty vehicles (Vojtisek-Lom et al., 2018), and ~2 times higher emissions than gas and ethanol (Borsari and Vicente de Assunção, 2017).
  - A range of trends has been observed in relation to fuel sulfur content:
    - SO_x generated from sulfur in fuel can cause long-term degradation of SCR systems and impact NH_3 slip (SAE, 2014b; Borsari and Vicente de Assunção, 2017).
    - After introduction of low-sulfur fuel standards in 2006, initial studies showed that lower sulfur fuels increased NH_3 emissions; but more recent studies have shown no impact on NH_3 emissions (Borsari and Vicente de Assunção, 2017) or even lower emissions when comparing ultra-low sulfur diesel to low-sulfur diesel (Borillo et al., 2015).
- **Driving conditions**
  - Trends in NH_3 emissions with different ranges of driving conditions have been observed to be similar to those for other mobile source exhaust emissions (Borsari and Vicente de Assunção, 2017; Sun et al., 2017 and 2014; Kean et al., 2009; Livingston et al., 2009; Durbin et al., 2001; Huai et al., 2003).
  - Examples of the typical trends observed include higher emissions with increased road grade, traffic congestion, and aggressive driving.

4.3 Emission Factors

NH_3 emission factors documented in the literature are briefly summarized in **Table 5**. For on-road light-duty vehicles, NH_3 emission factors reported in the literature are in the range of 0.005–0.14 g/mile for gasoline-powered vehicles, and 0.002–0.015 g/mile for diesel-powered vehicles. Perhaps surprisingly, available data for on-road heavy-duty vehicles is limited. For heavy-duty natural gas (NG)-powered tractors, NH_3 emission factors (using the Urban Dynamometer Driving Schedule test cycle) were found to be 0.38–0.89 g/mile, and for a NG-powered refuse truck, the NH_3 emission factor (using a refuse truck test cycle) was found to be 1.09 g/mile (Thiruvengadam et al., 2015). Operating conditions for three-way catalysts used in these NG-powered heavy-duty vehicles maximize the reduction of NOx but are also most conducive to production of NH_3 emissions.

Table 5. Summary of NH_3 emission factors for mobile sources.

Table Summary: This table summarizes mobile source NH_3 emission factors found in the literature or derived from emission inventory data.

Mobile Source Type	Fuel Type	NH_3 Emission Factor	Data Source
On-road light-duty vehicles	Gasoline	0.005–0.14 g/mile	Literature
On-road light-duty vehicles	Diesel	0.002–0.015 g/mile	Literature
On-road light-duty vehicles	Diesel	0.05 g/mile	Emission Inventory
On-road heavy-duty tractor	Natural gas	0.38–0.89 g/mile	Literature
On-road heavy-duty refuse truck	Natural gas	1.09 g/mile	Literature
On-road heavy-duty vehicles	Diesel	< 2 ppm (with AMOX catalyst)	Literature
On-road heavy-duty trucks	All fuel types	0.15 g/mile	Emission Inventory
On-road heavy-duty trucks	Diesel	0.17 g/mile	Emission Inventory
Off-road equipment	Diesel	0.08 g/gallon	Emission Inventory

A simple vehicle miles traveled (VMT)-weighted averaging across different vehicle classes and fuel types in the CARB EMFAC2021 v1.0.2 on-road emissions inventory produces estimates of 2020 NH_3 emission factors in California equal to 0.15 g/mile for heavy-duty trucks in general, and 0.17 g/mile for diesel-powered heavy-duty trucks. The corresponding NH_3 emission factor for diesel-powered non-trucks is 0.05 g/mile. These fleet-averaged emission factors are not consistent with the literature values reported above, but the diesel vehicle fleet in EMFAC2021 for year 2020 may include a larger number of newer trucks with SCR systems compared to the fleets studied in the literature. Diesel trucks equipped with SCR systems will have much higher NH_3 emissions compared to older trucks that do not have SCR systems.

Heavy-duty on-road diesel vehicles equipped with an AMOX catalyst to control NH_3 slip emissions were reported to have average NH_3 tailpipe concentrations of less than 2 parts per million (ppm) (Khalek et al., 2015; Mendoza-Villafuerte et al., 2017). Use of an AMOX catalyst on a heavy-duty vehicle was reported to result in NH_3 emissions that were as much as 7 times less than those from a similar vehicle without an AMOX catalyst (Mendoza-Villafuerte et al., 2017).

Reports of NH_3 emission factors from off-road mobile sources were not found in the most recent literature, and such data or estimates are primarily either embedded in emission inventories or provided in EPA documentation. For diesel-powered off-road equipment, NH_3 emission factors reported by EPA average about 0.08 g per gallon of fuel consumed (EPA, 2004). In the CARB OFFROAD2021 v1.0.5 emission inventory, NH_3 emission factors for diesel-powered off-road equipment also average about 0.08 g/gallon of fuel consumed (these were possibly based on EPA's reported values).

4.4 Contributions to Ambient Concentrations

Concentrations of NH_3 in ambient air have been the subject of many scientific studies that have produced similar results. NH_3 concentrations vary dramatically over different seasons. Concentrations in the summer are significantly greater than in the winter – one study showed that they were roughly 2–10 times greater (Yamamoto et al., 1967). The seasonal variation was found to be very similar to that of average air temperatures, and showed a periodic pattern over a year (Petrus et al., 2022; Yamamoto et al., 1967). NH_3 concentrations also exhibit a daily cycle associated with vehicular traffic, and a diurnal cycle of morning and afternoon concentration peaks has been correlated with morning and afternoon peak traffic in several urban areas (Petrus et al., 2022; Hu et al., 2014; Meng et al., 2011; Whitehead et al., 2007). This has been cited as evidence that motor vehicles may be a significant and dominant source of NH_3 emissions in urban areas.

Conflicting results on the relative contribution of mobile sources to NH_3 concentrations are present in the literature, which may indicate a dependence on local pollution composition and meteorology. One study conducted along a busy highway in Toronto, Canada, concluded that on-road emissions of NH_3 are negligible compared to the other sources in the area (Yao et al., 2013). Another study completed in Tokyo, Japan, concluded that non-vehicular sources were nearly the same as vehicular emissions (Osada et al., 2019). Multiple studies, including one conducted in Seoul, South Korea, and one in Bucharest, Romania, have concluded that urban NH_3 concentrations are highly correlated to the number of vehicles (Petrus et al., 2022; Phan et al., 2013). The impact of vehicles on seasonal variation in NH_3 concentrations is more consistent across the literature. Emissions from on-road sources were found to be an important source of NH_3 concentrations during the winter, while other sources were found to be more important during the summer (Meng et al., 2011; Whitehead et al., 2007).

5. Air Quality and Climate Impacts Associated with NH_3 Emissions

The major concern regarding air quality and climate impacts associated with NH_3 slip emissions from mobile sources is the subsequent formation of $PM_{2.5}$ that was discussed in the Introduction. About a dozen relevant references on the air quality impacts associated with NH_3 emissions were found in the literature (refer to Appendix A). Four of those also discussed associated climate impacts, and one additional reference on climate impacts was reviewed. Some studies investigated the excess nitrogen deposition to the environment resulting from NH_3 emissions, either directly from the gas phase or as particulate nitrate, but this document focuses on the impacts associated with NH_3 and subsequently formed $PM_{2.5}$ concentrations in air.

Key findings on the air quality and climate impacts associated with NH_3 emissions that were reported in the literature reviewed are provided below:

"Considering the high fraction of particulate NH_4NO_3, vehicular emissions of both NO_x and NH_3 contribute to high $PM_{2.5}$ events during winter in metropolitan Tokyo." (Osada et al., 2019)

"The overall scientific convergence clearly suggests that NH_3 should be targeted for the effective reduction of $PM_{2.5}$. It has been observed that horizontal concentration profiles show a decrease in concentrations with increasing distance from the source." (Behera et al., 2013)

"The aerosol pH plays an important role in the reactive uptake and release of gases, which can affect ozone chemistry, particle properties such as hygroscopic growth and scattering efficiency of sunlight and deposition processes. The impact of NH_3 emission reduction on $PM_{2.5}$ concentrations is strongest in winter. This is related to the enhanced NH_4NO_3 partitioning in the gas phase due to the higher temperatures in summer, so that a reduction of NH_3 influences the gas-phase concentrations more strongly than the particulate phase during this season. The opposite happens during the winter season." (Pozzer et al., 2017)

"Reductions in ammonia emissions affect gaseous ammonia concentrations close to the emissions site, but substantial impacts on particulate matter and atmospheric deposition often occur at considerable distances downwind." (Makar et al., 2009)

"The [particle] nucleation rates were highly sensitive to small additions of ammonia up to about 100 [parts per thousand by volume] p.p.t.v., with evidence of saturation at higher mixing ratios." (Kirkby et al., 2011)

"Vehicle NH_3 emissions are greater than agricultural emissions in counties containing near half of the U.S. population. Because of its low molecular weight, NH_3/ammonium has a more significant impact on molar-based aerosol chemical and optical properties than the same mass of nitrate, sulfate, or organic compounds. Because the lifetime of NH_3 can be as low as 0.5 day, the local emissions in cities will be disproportionately important to aerosol formation and urban nitrogen deposition than the transport from distant agricultural sources." (Sun et al., 2017)

"Ammonia preferentially neutralizes sulfate, the gas-particle partitioning of nitrate is shifted toward the gas phase when the sulfate concentration is high, and toward the aerosol phase when sulfate concentrations are low. Consequently, as SO_2 emissions are reduced and the concentration of sulfate aerosol decreases, some of the vapor

phase nitric acid may transfer to the aerosol phase, with the effect that some of the sulfate mass expected to be reduced is replaced with nitrate mass." (Seinfeld, 2004)

"Climate change, alone, with no emissions growth or controls has a small effect on the [maximum daily 8-hour ozone] $M8hO_3$ and $PM_{2.5}$ levels although changes in stagnation events, leading to higher pollutant concentrations over a slightly extended duration, may be regionally important. Future levels of sulfate, nitrate and ammonium are simulated to be significantly lower compared to organic carbon, leaving organic carbon as the likely major constituent of fine particulate matter in the far future." (Tagaris et al., 2007)

6. Health Risks Associated with NH_3 Emissions

The NH_3 RfC of 0.5 mg/m^3 set by the EPA in 2016 is based on four cross-sectional epidemiology studies conducted in occupational settings, specifically at urea fertilizer plants and a soda ash plant. Three of the studies found adverse health effects, and one did not. The EPA selected the study that did not find adverse health effects as the point of departure for determining the non-cancer RfC. In one of the three studies that found increases in respiratory impacts from NH_3, Rahman et al. (2007) evaluated workers in two urea fertilizer plants and observed greater respiratory symptoms and decreased lung function in workers at the plant with an average NH_3 concentration of 18.5 mg/m^3, as compared to workers at a plant with an average NH_3 concentration of 4.9 mg/m^3. A second study considered two urea fertilizer plants in a cross-sectional design, finding an increase in the prevalence of respiratory symptoms in a plant with exposures that measured between 2 and 27 mg/m^3, while the second plant had lower exposure levels, between 0.02 and 7 mg/m^3, and there was no increase in respiratory symptoms (Ballal et al., 1998). An additional study by the same research team found decreased lung function for workers with greater lifetime exposures to NH_3 (Ali et al., 2001). The principal study for derivation of the RfC was a cross-sectional study conducted in a soda ash plant. In that study, the authors found no evidence of change in respiratory function among any of the exposed workers who had a mean exposure of 6.5 mg/m^3, as compared to the non-exposed control group (Holness et al., 1989). The EPA took the lower bound of the 95% confidence interval of the mean of the exposed workers to determine the no-observed-adverse-effect-level (NOEL) for continuous exposure as 4.9 mg/m^3, for which EPA calculated the RfC. The EPA report cites additional occupational studies, studies with controlled human exposures, and animal studies that found increased respiratory symptoms; these results were used to further support these finding.

Additional agencies have also set health-based guidelines for NH_3 exposure. The value set by the California OEHHA has a Chronic Reference Exposure Level (REL) of 0.2 mg/m^3, or 300 ppb, set in 2000 (OEHHA, 1999). The Occupational Safety and Health Administration's (OSHA) Permissible Exposure Limit (PEL) is set as a time-weighted average over an 8-hour workday at 35 mg/m^3, or 50 ppm (U.S. Center for Disease Control, 2019). OSHA recognizes that many of their PEL values are outdated and need to be revised to lower levels. The National Institute for Occupational Safety and Health's (NIOSH's) REL for the Time Weighted Average over an 8-hour day is 25 ppm (18 mg/m^3), while the Short Term limit, for no more that 15 minutes of exposure, is 35 ppm (27 mg/m^3) (NIOSH, 2019). In a review on sensory irritation, the threshold for sensory irritation in the eyes and airways ranged from 20-50 ppm (Nielsen et al., 2007).

Additional studies that have evaluated the toxicity of NH_3 are based on high levels in the body that are the result of medical conditions causing hyperammonemia. NH_3 is produced in humans as a result of metabolism, and is transported by blood to the liver, converted to urea, and removed by the urine. Hyperammonemia in adults generally results from liver failure, and in children it is caused from inherited or acquired disorders. Urea cycle disorder, an inherited condition, is the most common reason for hyperammonemia in children. For individuals with hyperammonemia, there are numerous toxic effects, most notably to the brain (Braissant et al., 2012), but also the liver (Dasarathy et al., 2016). These adverse impacts are unrelated to ambient exposures.

As NH_3 is produced by metabolism in our bodies, humans are a source of NH_3 to the air through both exhaled breath and dermal emissions (Li et al., 2020). As a result, indoor ozone concentrations are typically higher than outdoor concentrations. In dense urban settings, particularly in hot regions, transport of indoor generated NH_3 can contribute a small percentage (2-5%) to the overall sources of NH_3 (Zheng et al., 2012).

Increasing concern recently over NH_3 emissions and the resulting health impacts are related to the impact of $PM_{2.5}$ generated from NH_3, not the toxicity of NH_3 itself. For example, a cost-benefit analysis for reducing NH_3 globally was conducted and published in the journal *Science* in 2021, and only considered the health impacts of NH_3-generated $PM_{2.5}$ (Gu et al., 2021). This study primarily considered the benefits from reducing NH_3 from agricultural sources. The EU has begun to regulate NH_3 emissions, focusing on emissions from agriculture. The authors noted that if adverse impacts were estimated using some of the newer PM-health relationships from the latest epidemiology studies, which have tended to find health impacts at lower concentrations, the health burden of NH_3 emissions would be increased. In their report on the assessment of mobile source NH_3 emissions in Los Angeles during the 2020 COVID-19 lockdown, Cao et al. (2022) noted that the health impacts of NH_3 emissions result from the adverse impacts of subsequently formed $PM_{2.5}$.

7. Conclusion and Recommendations

The literature review summarized in this technical memorandum was conducted to help Caltrans understand the magnitude and nature of NH_3 emissions from on- and off-road mobile sources and potential related impacts of project specifications that introduce or require fuel and/or equipment to meet emissions standards. Caltrans recognized (1) that a growing body of literature that documents a large contribution of NH_3 emissions from on- and off-road mobile sources in urban areas in recent years is potentially connected to the increasing use of mobile-source NO_x-control systems to meet regulatory emissions standards, and (2) that project requirements to use off-road equipment that meet Tier 4 standards could potentially lead to project-level NH_3 emissions if the required equipment uses controls that produce NH_3 slip. For project-level air quality analyses, the magnitude of NH_3 emissions for the project and whether those emissions will lead to increased $PM_{2.5}$ concentrations is important to understand, given the associated impacts on air quality, climate, and health.

Review of the literature and emission inventory data indicates that although the mobile source contribution of NH_3 is clearly growing, the overall contribution is still relatively small compared to the historically major sources of NH_3 emissions (i.e., agriculture, CAF, and waste disposal). On-road mobile sources represent 2-8% of the statewide NH_3 emissions inventory. Off-road mobile sources represent only about ~1% of statewide mobile source NH_3 emissions, and those off-road equipment types that are commonly used for Caltrans construction projects represent << 1% of statewide mobile source NH_3 emissions. However, since mobile sources of NH_3 emissions are more dominant in urban areas than previously thought, this emerging issue should be revisited as more studies and updated emission inventories are published.

For future consideration, the ability to impact $PM_{2.5}$ concentrations by reducing mobile source NH_3 emissions will depend on the region of the state, including its major sources, chemistry regime, and meteorological conditions. For example, if agriculture, CAF, and/or waste disposal (i.e., typical major sources) produce NH_3-saturated conditions in an area, then reducing the mobile source contribution to that area may not be an effective control strategy. However, it is likely that in urban areas, NH_3 slip from mobile source emissions control systems will continue to become the dominant source of NH_3 without further consideration of implementing additional controls such as AMOX catalysts.

Appendix A: Summary of References

Table A. Summary of reviewed or considered literature on NH_3.

Table Summary: This table lists the journal articles, reports, and other types of documents that were considered for this literature review and indicates which key topics each document addresses.

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *Atmospheric Environment*	Yamamoto	1967	Seasonal variation of atmospheric ammonia and particulate ammonium concentrations in the urban atmosphere of Yokohama over a 5-year period	-	x	-	-	-
Journal - *Journal of Environmental Quality*	Luebs et al.	1974	Diurnal Fluctuation and Movement of Atmospheric Ammonia and Related Gases from Dairies	x	x	-	-	-
Journal – *American Industrial Hygiene Association Journal*	Holness et al.	1989	Acute and Chronic Respiratory Effects of Occupational Exposure to Ammonia	-	-	-	-	x
Report	U.S. EPA	1994	Development and Selection of Ammonia Emissions Factors	x	-	-	-	-
Report	U.S. EPA	1995	Control and Pollution Prevention Options for Ammonia Emissions. Chapter 4 - Fossil Fuel Combustion	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *Science of The Total Environment*	Samaras and Zierock	1995	Off-road vehicles: a comparison of emissions with those from road transport	x	-	-	-	-
Journal - *ACS Environ. Sci. Technol.*	Fraser and Cass	1998	Detection of Excess Ammonia Emissions from In-Use Vehicles and the Implications for Fine Particle Control	x	-	-	-	-
Journal - *The International Journal of Tuberculosis and Lung Disease*	Ballal et al.	1998	Bronchial asthma in two chemical fertilizer producing factories in Eastern Saudi Arabia	-	-	-	-	x
Report Appendix	California Office of Environmental Health Hazard Assessment (OEHHA)	1999	Appendix D.3 Chronic RELs and toxicity summaries using the previous version of the Hot Spots Risk Assessment guidelines	-	-	-	-	x
Conference - EPA Archived Emission Inventory Conferences and Workshops	Fu et al.	1999	Quality Improvement for Ammonia Emission Inventory	x	-	-	-	-
Journal - *ACS Environ. Sci. Technol.*	Kean et al.	2000	On-Road Measurement of Ammonia and Other Motor Vehicle Exhaust Emissions	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Committee Meeting report	National Oceanic and Atmospheric Administration (NOAA)	2000	Atmospheric Ammonia: Sources and Fate, A Review of Ongoing Federal Research and Future Needs	x	-	x	x	-
Textbook	Finlayson-Pitts and Pitts	2000	Chemistry of the upper and lower atmosphere. Chapter 11-A-8, Ammonia	-	x	-	-	-
Journal - *ACS Environ. Sci. Technol.*	Baum et al.	2001	Multicomponent Remote Sensing of Vehicle Exhaust by Dispersive Absorption Spectroscopy. 2. Direct On-Road Ammonia Measurements	x	-	-	-	-
Journal - *ACS Environ. Sci. Technol.*	Christensen and Westerholm	2001	Measurement of Regulated and Unregulated Exhaust Emissions from a Lawn Mower with and without an Oxidizing Catalyst: A Comparison of Two Different Fuels	x	-	-	-	-
Conference - EPA Archived Emission Inventory Conferences and Workshops	Durbin et al.	2001	Emissions of Ammonia from Light-Duty Vehicles	x	-	-	-	-
Journal - *International Journal of Occupational and Environmental Health*	Ali et al.	2001	Pulmonary function of workers exposed to ammonia: A study in the Eastern Province of Saudi Arabia	-	-	-	-	x
Journal - *SAE Transactions*	Shores et al.	2002	Measurement of ammonia emissions from EPA's instrumented vehicle	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Conference - 11th CRC On-road Vehicle Emissions Workshop	Gertler	2002	Emissions from Diesel and Gasoline Engines Measured in Highway Tunnels	x	-	-	-	-
Report	Sonoma Technology	2003	Recommended improvements to the CMU ammonia emission inventory model for use by LADCO	x	-	-	-	-
Conference - EPA Archived Emission Inventory Conferences and Workshops	Huai et al.	2003	Investigation of the formation of NH_3 ammonia emissions as a function of vehicle load and operating condition	x	-	-	-	-
Report	U.S. EPA	2004	Estimating ammonia emissions from anthropogenic nonagricultural sources	x	-	-	-	-
Conference - EPA Archived Emission Inventory Conferences and Workshops	Sonoma Technology	2004	Research and Development of Ammonia Emission Inventories for the Central States Regional Air Planning Association	x	-	-	-	-
Conference - EPA Archived Emission Inventory Conferences and Workshops	Roe et al.	2004	Emissions Inventory Guidance for Anthropogenic Non-Agricultural Ammonia Sources	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Regulatory Document	U.S. Department of Health and Human Services	2004	Toxicological Profile for Ammonia	-	-	-	-	x
Journal - *Atmospheric Environment*	Cape et al.	2004	Concentrations of ammonia and nitrogen dioxide at roadside verges, and their contribution to nitrogen deposition	-	x	x	-	-
Journal - *AIChE Journal*	Seinfeld	2004	Air Pollution: A Half Century of Progress	-	-	x	-	-
Journal - *ACS Environ. Sci. Technol.*	Burgard et al.	2006	Remote Sensing of Ammonia and Sulfur Dioxide from On-Road Light Duty Vehicles	x	-	x	-	-
Technical Report	SAE	2006	Ammonia Oxidation Catalysts for Mobile SCR Systems	x	-	-	-	-
Journal - *Water, Air, and Soil Pollution*	Whitehead et al.	2007	Seasonal and Diurnal Variation in Atmospheric Ammonia in an Urban Environment Measured Using a Quantum Cascade Laser Absorption Spectrometer	x	x	-	-	-
Journal - *Journal of Geophysical Research Atmospheres*	Tagaris et al.	2007	Impacts of global climate change and emissions on regional ozone and fine particulate matter concentrations over the United States	-	-	x	-	-
Journal – *Regul Toxicol Pharmacol*	Nielsen et al.	2007	Sensory irritation: risk assessment approaches	-	-	-	-	x

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *International Journal of Occupational and Environmental Health*	Rahman et al.	2007	Exposure to Ammonia and Acute Respiratory Effects in a Urea Fertilizer Factory	-	-	-	-	x
Journal - *Atmospheric Environment*	Kean et al.	2009	Trends in on-road vehicle emissions of ammonia	x	-	-	-	-
Journal - *Atmospheric Environment*	Livingston et al.	2009	Ammonia emissions from a representative in-use fleet of light and medium-duty vehicles in the California South Coast Air Basin	x	-	-	-	-
Journal - *Atmospheric Chemistry and Physics*	Makar et al.	2009	Modelling the impacts of ammonia emissions reductions on North American air quality	x	-	-	-	-
Journal - *Science*	Shindell et al.	2009	Improved attribution of climate forcing to emissions	-	-	-	x	-
Report	SAE	2011	Design and Durability of Vanadium-SCR Catalyst Systems in Mobile Off-Road Applications	x	-	-	-	-
Journal - *Atmos. Chem. Phys.*	Meng et al.	2011	Characteristics of atmospheric ammonia over Beijing, China	x	x	-	-	-
Journal - *Nature*	Kirkby et al.	2011	Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation	-	-	x	x	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *Journal of Inherited Metabolic Disease*	Braissant et al.	2012	Ammonia toxicity to the brain	-	-	-	-	x
Journal - *Atmospheric Chemistry and Physics*	Zheng et al.	2012	Development and uncertainty analysis of a high-resolution NH_3 emissions inventory and its implications with precipitation over the Pearl River Delta region, China	-	-	-	-	x
Journal - *Atmospheric Environment*	Yao et al.	2013	Is vehicular emission a significant contributor to ammonia in the urban atmosphere?	x	x	-	-	-
Journal - *Atmospheric Environment*	Phan et al.	2013	Analysis of ammonia variation in the urban atmosphere	x	x	-	-	-
Journal - *Environmental Science and Pollution Research*	Behera et al.	2013	Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies	-	-	x	-	-
Journal - *International Journal of Occupational and Environmental Health*	Ali et al.	2013	Pulmonary Function of Workers Exposed to Ammonia: A Study in the Eastern Province of Saudi Arabia	-	-	-	-	x
Journal - *ACS Environ. Sci. Technol.*	Sun et al.	2014	On-Road Ammonia Emissions Characterized by Mobile, Open-Path Measurements	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *Atmospheric Environment*	Hu et al.	2014	Variability of atmospheric ammonia related to potential emission sources in downtown Toronto, Canada	x	x	-	-	-
Technical Report	SAE	2014a	New Insights into the Unique Operation of Small Pore Cu-Zeolite SCR Catalyst: Overlapping NH_3 Desorption and Oxidation Characteristics for Minimizing Undesired Products	x	-	-	-	-
Technical Report	SAE	2014b	Impact of Sulfur-Oxides on the Ammonia Slip Catalyst Performance	x	-	-	-	-
Journal - *Atmospheric Environment*	Chen et al.	2014	Seasonal ambient ammonia and ammonium concentrations in a pilot IMPROVE NH_x monitoring network in the western United States	-	x	-	-	-
Journal - *IOP science*	Liu et al.	2014	Emission factor of ammonia (NH_3) from on-road vehicles in China: tunnel tests in urban Guangzhou	x	-	-	-	-
Journal - *ACS Environ. Sci. Technol.*	Borillo et al.	2015	Effectiveness of Selective Catalytic Reduction Systems on Reducing Gaseous Emissions from an Engine Using Diesel and Biodiesel Blends	x	-	-	-	-
Journal - *ACS Environ. Sci. Technol.*	Walters et al.	2015	Nitrogen Isotope Composition of Thermally Produced NO_x from Various Fossil-Fuel Combustion Sources	x	-	-	-	-
Journal - *Journal of Air and Waste Management Association*	Thiruvengadam et al.	2015	Unregulated greenhouse gas and ammonia emissions from current technology heavy-duty vehicles	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *Journal of Air and Waste Management Association*	Khalek et al.	2015	Regulated and unregulated emissions from modern 2010 emissions-compliant heavy-duty on-highway diesel engines	x	-	-	-	-
Journal - *ES&T*	Bishop and Stedman	2015	Reactive Nitrogen Species Emission Trends in Three Light-/Medium-Duty United States Fleets	x	-	-	-	-
White Paper - International Council on Clean Transportation (ICCT)	ICCT	2016	Technology pathways for diesel engines used in non-road vehicles and equipment	x	-	-	-	-
Textbook	Seinfeld and Pandis	2016	Atmospheric Chemistry and Physics - from air pollution to Climate Change. Chapter 2-3-4: Ammonia	-	x	-	-	-
Report	U.S. EPA	2016	Toxicological Review of Ammonia Noncancer Inhalation: Executive Summary	-	-	-	-	x
Journal - *Metabolic Brain Disease*	Dasarathy et al.	2016	Ammonia toxicity: from head to toe?	-	-	-	-	x
Journal - *Science of the Total Environment*	Mendoza-Villafuerte et al.	2017	NO_x, NH_3, N_2O and PN real driving emissions from a Euro VI heavy-duty vehicle. Impact of regulatory on-road test conditions on emissions	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *Transportation Research Part D: Transport and Environment*	Borsari and Vicente de Assunção	2017	Ammonia emissions from a light-duty vehicle	x	-	-	-	-
Journal - *ACS Environ. Sci. Technol.*	Sun et al.	2017	Vehicle Emissions as an Important Urban Ammonia Source in the United States and China	x	-	x	-	-
Journal - *Atmospheric Environment*	Suarez-Bertoa et al.	2017	On-road measurement of NH_3 emissions from gasoline and diesel passenger cars during real world driving conditions	x	x	-	-	-
Journal – *Atmospheric Chemistry and Physics*	Pozzer et al.	2017	Impact of agricultural emission reductions on fine-particulate matter and public health	-	-	x	-	-
Journal - *Science of the Total Environment*	Fenn et al.	2018	On-road emissions of ammonia: An underappreciated source of atmospheric nitrogen deposition	x	-	x	-	-
Journal - *Science of the Total Environment*	Vojtíšek-Lom et al.	2018	On-road and laboratory emissions of NO, NO_2, NH_3, N_2O and CH_4 from late-model EU light utility vehicles: Comparison of diesel and CNG	x	-	-	-	-
Journal - *Science of the total Environment*	Triantafyllopoulos et al.	2018	Experimental assessment of the potential to decrease diesel NO_x emissions beyond minimum requirements for Euro 6 Real Drive Emissions (RDE) compliance	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *Atmospheric Environment*	Osada et al.	2019	Vehicular exhaust contributions to high NH_3 and $PM_{2.5}$ concentrations during winter in Tokyo, Japan	x	x	x	-	-
White Paper - ICCT	ICCT	2019	Beyond NO_x: Emissions of unregulated pollutants from a modern gasoline car	x	-	-	-	-
Website	U.S. Center for Disease Control	2019	The National Institute for Occupational Safety and Health (NIOSH) – NIOSH Pocket Guide to Chemical Hazards: Ammonia	-	-	-	-	x
Journal - *Environmental Sciences Europe*	Giannakis et al.	2019	Costs and benefits of agricultural ammonia emission abatement options for compliance with European air quality regulations	-	-	-	-	x
Website	U.S. EPA	2020	2020 National Emissions Inventory (NEI) Data	x	-	-	-	-
Journal - *ACS Environ. Sci. Technol.*	Farren et al.	2020	Underestimated Ammonia Emissions from Road Vehicles	x	-	-	-	-
Policy Brief	The Royal Society	2020	Ammonia: zero-carbon fertiliser, fuel and energy store	-	-	x	x	x
Journal - *ACS Environ. Sci. Technol.*	Li et al.	2020	Human Ammonia Emission Rates under Various Indoor Environmental Conditions	-	-	-	-	x
Fact sheet	National Atmospheric Deposition Program	2020	**Ammonia Monitoring Network fact sheet** (https://nadp.slh.wisc.edu/wp-content/uploads/2020/11/AMoNsheet.pdf), accessed 11/21/2023	-	x	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *Atmospheric Environment: X*	Farren et al.	2021	Characterisation of ammonia emissions from gasoline and gasoline hybrid passenger cars	x	-	-	-	-
Journal - *Journal of Environmental Sciences*	Liu et al.	2021	Research on ammonia emissions characteristics from light-duty gasoline vehicles	x	-	-	-	-
Thesis	Abualqumboz	2021	Ammonia Emission Assessment from Gasoline and Diesel Engines Under Utah Specific Conditions	x	-	-	-	-
Report	ERG	2021	Development of Texas Nonroad Model Mobile Source Air Emissions Reporting Requirements, Reasonable Further Progress, and Redesignation and Maintenance Emissions Inventories	x	-	-	-	-
Journal - *Science*	Gu et al.	2021	Abating ammonia is more cost-effective than nitrogen oxides for mitigating $PM_{2.5}$ air pollution	-	-	-	-	x
Journal - *ACS Environ. Sci. Technol.*	Wyer et al.	2022	Ammonia emissions from agriculture and their contribution to fine particulate matter: A review of implications for human health	-	-	x	x	x
Journal - *Atmospheric Pollution Research*	Abualqumboz et al.	2022	On-road tailpipe characterization of exhaust ammonia emissions from in-use light-duty gasoline motor vehicles	x	-	-	-	-
Journal - *Sustainability*	Giechaskiel et al.	2022	Effect of Tampering on On-Road and Off-Road Diesel Vehicle Emissions	x	-	-	-	-
Report	SCAQMD	2022	Clean Fuels Program Annual Report	x	-	-	-	-

Type of Document	Author	Year	Title	Emissions	Concentrations (in ambient air)	Air Quality Impacts	Climate Impacts	Health Risks
Journal - *MDPI Air*	Hagan et al.	2022	Non-Road Mobile Machinery Emissions and Regulations: A Review	x	-	-	-	-
Journal - *Nature*	Chen et al.	2022	Significant contributions of combustion-related sources to ammonia emissions	x	-	-	-	-
Journal - *Environ. Sci. Technol. Letters*	Cao et al.	2022	COVID-19 Lockdowns Afford the First Satellite-Based Confirmation That Vehicles Are an Under-recognized Source of Urban NH_3 Pollution in Los Angeles	x	x	-	-	x
Journal - *Atmos. Chem. Phys.*	Wen et al.	2022	Vehicular ammonia emissions: An underappreciated emission source in densely-populated areas	x	-	-	-	-
Journal - *Materials*	Petrus et al.	2022	Ammonia Concentration in Ambient Air in a Peri-Urban Area Using a Laser Photoacoustic Spectroscopy Detector	-	x	-	-	-
Journal - *EGUsphere*	Wang	2023	Bridging the spatial gaps of the Ammonia Monitoring Network using satellite ammonia measurements	-	x	-	-	-
Report	CARB	2023	Ammonia: Supplemental Information for EPA in Support of 15 µg/m^3 Annual $PM_{2.5}$ Standard	x	x	x	-	-
Website	CARB	2023a	Criteria Pollutant Emission Inventory Data - California Emissions Projection Analysis Model	x	-	-	-	-
Website	CARB	2023b	EMission FACtor (EMFAC) website	x	-	-	-	-

Caltrans Technical Report Documentation Page

1. Report No.:	CTAQ-TM-24-435.03.01
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3. Report Phase and Edition:	Final
4. Title and Subtitle:	Literature Review of Ammonia Emissions from On- and Off-Road Mobile Sources
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7. Caltrans Project Coordinator(s):	Daisy Laurino, PE
8. Performing Organization Names and Addresses:	California Department of Transportation Division of Environmental Analysis, MS-27 1120 N Street P.O. Box 942874 Sacramento, CA 94274-0001 http://www.dot.ca.gov/env/air/
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18. Abstract:

This technical memorandum summarizes the results of a literature review focused on ammonia (NH_3) emissions from on- and off-road mobile sources, as well as associated

ambient air concentrations of NH_3, air quality and climate impacts, and health risks. The literature review was conducted to help Caltrans understand (1) the extent to which certain technologies for controlling exhaust emissions of nitrogen oxides (NO_x) from on- and off-road mobile source engines result in exhaust emissions of NH_3; and (2) potential adverse impacts of project specifications that introduce or require fuel and/or equipment to meet requirements of the California Low Carbon Fuel Standard (LCFS) regulation. The document (1) provides background information on NH_3 emissions; (2) presents the search strategy used for the literature review and an overview of the relevant literature found; (3) describes relevant studies and available data on NH_3 emissions from on- and off-road mobile sources and options for controlling those emissions; (4) provides a brief discussion of air quality and climate impacts associated with NH_3 emissions; (5) describes health risks associated with NH_3 emissions; and (6) summarizes the key findings of the literature review and recommendations for further consideration.