MOVES3 Sensitivity Analysis

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This analysis tested the sensitivity of the latest version of the U.S. Environmental Protection Agency's Motor Vehicle Emissions Simulator (MOVES), MOVES3, to various inputs. The analysis focuses on the following county level inputs: hotelling, off-network idle (ONI), average speed distribution, and age distribution as well as additional specific inventory focus areas (light-duty versus heavy-duty vehicles, off-network versus restricted versus unrestricted road types, and urban versus rural road types) in response to the changes made to the four inputs. Sensitivity of each input was assessed by evaluating the range of percent changes of different testing scenarios compared to a reference case emissions inventory. Results showed that age distribution and speed distribution have the greatest sensitivities across the chosen pollutant emission inventories, while ONI and hotelling have modest sensitivities. The results of this sensitivity testing may be of interest to those using MOVES to model onroad emissions of criteria pollutants, air toxics, and greenhouse gases.</td></tr>
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List of Abbreviations

Abbreviation	Term
APU	Auxiliary power units
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2eq	Carbon dioxide equivalents
CRC	Coordinating Research Council
EPA	Environmental Protection Agency
FC	Functional class
FHWA	Federal Highway Administration
FIPS	Federal Information Processing System
GHG	Greenhouse gas
HD	Heavy-duty
HDV	Heavy-duty vehicle
HHD	Heavy heavy-duty
HPMS	Highway Performance Management System
LD	Light-duty
LDV	Light-duty vehicle
LOS	Level of service
MOVES	Motor Vehicle Emissions Simulator
MSAT	Mobile Source Air Toxics
NCHRP	National Cooperative Highway Research Program
NEI	National emissions inventory
NO_x	Nitrogen oxides
ONI	Off-network idle
PM_{10}	Particulate matter 10 micrometers or less
$PM_{2.5}$	Particulate matter 2.5 micrometers or less
RMAR	Relative mileage accumulation rates
SAFE	Safer Affordable Fuel-Efficient
SHI	Source hours idling
SHO	Source hours operating
SIP	State Implementation Plan
TIF	Total idle fraction
TSE	Truck stop electrification
VMT	Vehicle miles traveled
VOC	Volatile organic compounds

Executive Summary

This MOVES3 Sensitivity Analysis details the effort undertaken by the Volpe Center and the Federal Highway Administration's Office of the Natural Environment to assess the sensitivity of the latest version of the U.S. Environmental Protection Agency's (EPA's) MOtor Vehicle Emissions Simulator (MOVES), MOVES3, to various inputs. MOVES3 incorporates new regulations, data, and model features (see details in Background & Purpose section). The results of this sensitivity testing may be of interest to those using MOVES to model onroad emissions of criteria pollutants, air toxics, and greenhouse gases. Though this sensitivity analysis further emphasizes the importance of using local inputs to generate the most accurate emission inventories, the information provided in this report may help stakeholders prioritize data collection and assist in interpreting results.

The analysis focuses on the following county level inputs:

- hotelling,
- off-network idle (ONI),
- average speed distribution, and
- vehicle age distribution.

Sensitivity scenarios were created by modifying input datasets to simulate a range of scenarios and region-specific data for the four chosen inputs. The adjustments to specific inputs were meant to bound a wide range of local conditions or local policies; they were not meant to be a realistic set of conditions for a specific county or region. Testing was conducted for a base year of 2020 and a series of future years through 2060.

Table 1 summarizes the overall sensitivity of the model to the four inputs for each pollutant in the total emissions inventory[1].

Table 1. Summary of MOVES Inputs & Sensitivity Ranges

Sensitivity Range	**VOC**	**NO_x**	**$PM_{2.5}$**	**PM_{10}**	**CO_2eq**	**CO**
Very Substantial (>50%)	n/a	Speed	Speed	Speed	n/a	n/a
Substantial (15-50%)	Speed, Age	Age	n/a	n/a	Speed	Speed, Age
Moderate (5-15%)	n/a	ONI	Age	n/a	ONI	n/a
Modest (<5%)	ONI, Hotelling	Hotelling	ONI, Hotelling	ONI, Hotelling, Age	Age, Hotelling	ONI, Hotelling

[1] For the total inventory results, emissions inventory results for individual pollutants were summed across the whole county (including all source types, processes, and road types). Sensitivity of each input was assessed by evaluating the range of percent changes of different testing scenarios compared to a reference case emissions inventory.

Additional analyses highlight the range of sensitivities in specific inventory focus areas (light-duty versus heavy-duty vehicles, off-network versus restricted versus unrestricted road types, and urban versus rural road types) in response to the changes made to the four inputs. Sensitivities for specific groups of vehicle types and activity types include the following:

- Analysis year:
  - For total inventory analysis, age distribution shows higher sensitivity for all vehicle types in the near-term due to effects of regulatory actions.
- Heavy-duty vehicle sensitivity to average speed:
  - MOVES3 has updated running rates for heavy-duty diesel vehicles that are meant to represent less effective NO_x controls during idle, low speeds, and low power operations. Under congested traffic conditions, MOVES3 users should expect higher NO_x emissions for these vehicle types compared to conditions with faster speed distributions.
- Hotelling and combination long-haul trucks:
  - Hotelling is only applicable to combination long-haul trucks, therefore changes in hotelling characteristics typically result in very small percent differences in the aggregate inventory from the reference case (a MOVES run with inputs that represent a “generic” county and base case conditions).
- Off-network and average speed:
  - For off-network inventories, ONI has a substantial impact on NO_x and a very substantial impact on CO_2eq.
  - Average speed scenarios show a greater negative percent difference for $PM_{2.5}$, NO_x, and CO_2eq for off-network inventories. These results align with the expectation that the overall average speed distributions will affect the total number of hours idling on and off the roadway network when the lowest speed bin distribution changes. Section 4.12 in EPA’s MOVES3 Technical Guidance provides recommendations on using the off-network idling input tables in county level MOVES runs. [1]

Background & Purpose

This document examines the sensitivity of emission results to changes in various inputs in the latest version of the U.S. Environmental Protection Agency's (EPA's) Motor Vehicle Emissions Simulator (MOVES). The third major release of MOVES (MOVES3) incorporates new regulations, data, and model features, including new data on light-duty and heavy-duty vehicle emissions and impacts of the 2020 Safer Affordable Fuel-Efficient (SAFE) Rule for cars and light-duty trucks and the 2016 Heavy-Duty Greenhouse Gas Phase 2 Rule. EPA made a number of changes to MOVES3 including the elimination of specific ramp modeling, updated extended idling assumptions, and a new idling feature to estimate idle emissions outside of the normal drive cycle (e.g., idling in parking lots, or freight facilities). [2]

This document will inform MOVES3 users about the sensitivity of emissions inventories to select inputs in the most recent MOVES3 version available at the time of analysis. [2] [3] [4] The analysis focused on inputs that either changed significantly from MOVES2014b or are expected to have a high impact on the resulting emissions inventory based on previous MOVES sensitivity analyses. The four chosen inputs are:

- hotelling – default hotelling estimate methodology now based on rural and urban restricted VMT in MOVES3,
- off-network idle (ONI) – new input in MOVES3,
- average speed distribution – high sensitivity of emissions outputs to this input based on previous studies, and
- vehicle age distribution – high sensitivity of emissions outputs to this input based on previous studies.

Variation in the inputs was modeled through modifying reference (base) case input datasets to encompass a range of scenarios and region-specific data. Reference cases are described more fully in the Methodology section, and a full listing of the reference case MOVES inputs can be found in Appendix A – MOVES Run Specifications. The testing focused on the magnitude of changes in the total emissions inventories for the following pollutants:

- volatile organic compounds (VOCs),
- nitrogen oxides (NO_x),
- carbon monoxide (CO),
- particulate matter (PM) sized 2.5 micrometers in diameter and smaller ($PM_{2.5}$), including brake and tire wear PM,
- PM sized 10 micrometers in diameter and smaller (PM_{10}), including brake and tire wear PM,
- carbon dioxide equivalents (CO_2eq), and
- Mobile Source Air Toxics (MSATs), including benzene, ethanol, naphthalene particle and gas, 1,3-butadiene, formaldehyde, acetaldehyde, and acrolein.

Sensitivity of each input was assessed by comparing the range of percent change of all scenarios associated with a particular input to the reference case (a MOVES run with inputs that represent a "generic" county and base case conditions) emissions inventory. Each input was categorized by its relative effect—very substantial (greater than 50%), substantial (15-50%), moderate (5-15%), and

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[2] All runs for this study used MOVES3.0.2, released in September 2021. See Latest Version of MOtor Vehicle Emission Simulator (MOVES) | US EPA. [3] For a complete update log, see the MOVES3 update log | US EPA. [4]

modest (less than 5%)—on the emission inventories across the different pollutants and testing years. Post-processing aggregation highlighted the range of sensitivities in specific inventory focus areas (light-duty versus heavy-duty vehicles, off-network versus restricted versus unrestricted road types, and urban versus rural road types) in response to the changes made to the four inputs.

This report is intended to provide stakeholders from state and local agencies with information that could inform prioritizing collection of local data for use as inputs to MOVES runs based on the sensitivity of MOVES3 specifically to selected inputs. These results may provide insight into how changes in MOVES3 could affect local agencies' onroad emissions modeling.

The results and trends shown in this report are intended to demonstrate the general sensitivity of various MOVES3 inputs and should not in any way be used to meet any regulatory requirements, such as State Implementation Plans (SIPs) or transportation conformity. Users should be aware that local inputs (such as fuels, meteorology, IM program, etc.) will have a significant impact on sensitivity shown for the various inputs. To fully understand the potential impact of changes to MOVES inputs, an area-specific analysis should be completed with local inputs.

Methodology

Methodology of the sensitivity testing is detailed in the sections below:

1. Reference case inputs: development of reference (baseline) case input database at the county-level, and the execution of the reference case MOVES3 run
2. Scenario modeling: scenario definition to capture the new functionality and high-impact components of MOVES3, the development of scenario-specific inputs and run specifications, and the execution of the reference case MOVES3 runs
3. Post-processing: post-processing of output data to show ranges in sensitivities for each input and review of output for quality assurance

Reference Case Inputs

The reference case was created by developing a county-level database using national defaults and representative local data. Custom domain is no longer available in MOVES3, so a specific county was selected for the reference and sensitivity scenarios. For this analysis, we selected Middlesex County in Massachusetts (FIPS code 25017) as a "generic" county by using national distribution inputs (e.g., monthly VMT distributions, hourly VMT distributions, etc.) for county inputs as well as some county-specific data including VMT and vehicle population. Fuel type distributions as well as temperature and humidity data are also specific to Middlesex for these reference case runs. The reference case used a calendar year of 2020 as the baseline and the following future years: 2024, 2027, 2030, 2033, 2038, 2040, 2050, and 2060. These future years were intended to cover both near-term modeling needs (e.g., Transportation Conformity and SIP modeling) and some further out-modeling purposes (e.g., GHG modeling). This study used MOVES3.0.2 for creation of the reference case and all subsequent runs.

For specific details on the configuration of the MOVES3 reference case run (runspec) and the mix of national and county-specific data used as input to the reference case, refer to Appendix A – MOVES Run Specifications.

Scenarios Modeled

Sensitivity analyses were performed on the following inputs: hotelling, off-network idle (ONI), average speed distribution, and vehicle age distribution. Table 2 provides a description of the different testing scenarios for each input, and Table 3 documents the changes made to the input in MOVES3 as compared to MOVES2014.

For each scenario, the relevant county data input table(s) were updated and a new MOVES runspec was created for each scenario and year combination. For the average speed distribution scenarios, the functional class (FC) and level of service (LOS) combinations selected represent a range of conditions from free flowing traffic to highly congested traffic depending on the road type[3]. This study used MOVES3.0.2 for all runs, and the total number of MOVES runs[4] across all scenarios and years was 234. Given the large number of input databases, runspecs, and individual MOVES runs, scripts were used to generate inputs and runspecs and ultimately run MOVES. The adjustments to specific inputs (e.g., hotellingActivityDistribution for the hotelling scenarios or sourceTypeAgeDistribution for the age distribution scenarios) were meant to bound a wide range of local conditions or local policies; they were not meant to be a realistic set of conditions for a specific county or region. For more details on the scenario inputs refer to Appendix B – Scenario Development.

Table 2. Modeling Scenarios

Input	Scenario No.	Description
Hotelling	Reference	MOVES national default distribution (e.g., 73% extended idle, 7% diesel APU, 0% battery, 20% engine off for model years 2010-2020)
Hotelling	1	Use 100% extended idling for hotelling activity
Hotelling	2	Use 50% extended idling and 50% diesel auxiliary power units (APU) for hotelling
Hotelling	3	Use 100% diesel APU for hotelling
Hotelling	4	Use 100% truck stop electrification (TSE) or battery APU for hotelling
Off-network idle (ONI)	Reference	MOVES national default distribution[5] [5]
Off-network idle (ONI)	5	25% idle decrease for heavy-duty (HD) vehicle source types (41-62)
Off-network idle (ONI)	6	75% idle decrease for HD vehicle source types (41-62)
Off-network idle (ONI)	7	25% idle decrease for all source types

[3] Each average speed distribution was mapped to both urban and rural roads for all source types. For example, in scenario 11B, the average speed distribution based on FC11 LOS B (different function classes (FC) and levels of service (LOS) are described in the *Highway Capacity Manual*) replaced the reference average speed distributions on both urban restricted access (road type 4) and rural restricted access (road type 2) for all source types.

[4] Each scenario and modeling year is a separate MOVES3 run. For the average speed distribution scenarios, each scenario number, LOS, and year (e.g., scenario 11B 2040) is a separate MOVES3 run. The total number of average speed scenarios is the total of the 5 levels of service in scenario 11, the 3 levels of service in scenario 12, and the 3 levels of service in scenario 13, or 11 total per model year.

[5] The off-network idling inputs and the default scale national average values for this input data are described fully in EPA's MOVES Population and Activity Report. [5]

Off-network idle (ONI)	8	75% idle decrease for all source types
Off-network idle (ONI)	9	50% idle decrease for transit buses, engine off after 5 minutes
Off-network idle (ONI)	10	90% idle decrease for transit buses, engine off after 5 minutes
Average speed distribution	Reference	MOVES national default distribution by source type and road type
Average speed distribution	11: 11b – 11f	Urban and Rural restricted road type both using same Urban interstate speed distribution; scenario letter corresponds to LOS B - F
Average speed distribution	12: 12c-12e	Urban and Rural unrestricted road type both using same Urban principal arterial freeway speed distribution; scenario letter corresponds to LOS C - E
Average speed distribution	13: 13b, 13c, 13f	Urban and Rural unrestricted road type both using same Urban principal arterial other speed distribution; scenario letter corresponds to LOS B, C, F
Vehicle Age distribution	Reference	MOVES national default distribution by source type
Vehicle Age distribution	14	Increase Group 1 fractions by 10% and decrease Groups 2 and 3 proportionally. This represents a small shift to newer vehicles as compared to the national average.
Vehicle Age distribution	15	Increase Group 1 fractions by 25% and decrease Groups 2 and 3 proportionally. This represents a larger shift to newer vehicles as compared to the national average.
Vehicle Age distribution	16	Decrease Group 1 fractions by 10% and increase Groups 2 and 3 proportionally. This represents a small shift to older vehicles as compared to the national average.
Vehicle Age distribution	17	Decrease Group 1 fractions by 25% and increase Groups 2 and 3 proportionally. This represents a larger shift to older vehicles as compared to the national average.

Table 3. MOVES3 Updates by Input

Input	Description of MOVES3 Updates
Hotelling	Updated extended idle and auxiliary power estimates. Default scale hotelling estimate methodology now based on rural and urban restricted VMT.
Off-network idle (ONI)	New input developed from latest telematics data

Average speed distribution	Some updates, but not fundamentally different from MOVES2014b
Vehicle Age distribution	New registration data, but not fundamentally different from MOVES2014b

Post-Processing Details

The data processing steps for this analysis were intended to provide a comprehensive dataset containing all of the results from all scenarios and all years. The goal was to make this dataset flexible for multiple purposes, including potential follow-up analyses beyond the overall inventory analysis discussed in this report.

To obtain a comprehensive, granular dataset, post-processing of the MOVES output data was performed using Python scripts. Post-processing focused on combining results from the scenario and year output databases and joining emissions inventories with relevant activity data to obtain a comprehensive dataset with all of the scenario and year combinations. Emissions results were generated for all on-road emission process types[6], and aggregated according to the type of activity which best accounted for the emissions for that process and road type. For example, start exhaust and crankcase start exhaust emissions (process ids 2, 16) were aggregated and joined with total start activity for each vehicle type, model year, and fuel type, on the off-network road type. For more specific details on the post-processing steps and the format of the resulting dataset, including which emissions processes were matched to which activity types, refer to Table 7 in Appendix C – Post-Processing.

The resulting dataset contains a record for each vehicle type, model year, fuel type, road type, and pollutant combination for various activity types including MOVES-Calculated distance traveled (VMT), starts, off-network idling, vehicle population, and hotelling. The values of these activity types in each record were calculated by MOVES starting from the county-level default inputs specific to Middlesex County for annual VMT by HPMS vehicle type and overall vehicle populations. These records report the aggregate emissions for all processes relevant to the reported activity type, but without repeating or "double counting" emissions. Total emissions inventories can be obtained by summing all emissions for a specific year and scenario combination. This final output format also allows for other types of analysis in the future. For example, one could compare emissions factors instead of inventories for the different types of activities across scenarios and years, or even different vehicle types and model years.

[6] Process types refers to vehicle processes that produce emissions, such as exhaust from running and starts, brake wear or tire wear, or evaporation during refueling. Appendix D shows the process names for the process IDs used in MOVES.

Results and Discussion

Inventory Total

To see general trends, each input was categorized by its relative effect on the emission inventories across the different pollutants and testing years. Sensitivity of each input (hotelling, ONI, speed distribution, and age distribution) was assessed by comparing the range of percent change of all scenario inventories of that specific input to the reference case emissions inventory. For the total results, emissions inventory results for individual pollutants were summed across the entire county (including all source types, processes, and road types). Table 4 highlights the relative sensitivity of each input for each pollutant, represented by the percent difference of the range of all scenarios to the reference case.[7]

Table 4. Summary of MOVES Inputs & Sensitivity Ranges

Sensitivity Range	**VOC**	**NO_x**	**$PM_{2.5}$**	**PM_{10}**	**CO_2eq**	**CO**
Very Substantial (>50%)	n/a	Speed	Speed	Speed	n/a	n/a
Substantial (15-50%)	Speed, Age	Age	n/a	n/a	Speed	Speed, Age
Moderate (5-15%)	n/a	ONI	Age	n/a	ONI	n/a
Modest (<5%)	ONI, Hotelling	Hotelling	ONI, Hotelling	ONI, Hotelling, Age	Age, Hotelling	ONI, Hotelling

Figure 1, Figure 3, and Figure 4 show the percent difference from the reference case (top plot) and the summed emissions inventory of different scenario groupings (bottom plot) for NOx, PM2.5[8], and CO2eq respectively. In each of these figures, the bottom plot shows the range between the minimum and maximum scenario in each sensitivity case. For example, the bottom of the age distribution bar in 2020 (Figure 1) corresponds to scenario 15 (Figure 2), a significantly younger fleet, and the top of the age distribution bar corresponds to scenario 17, a significantly older fleet. In each of these figures the top plot shows the minimum and maximum percent difference from the reference case for each year and input. To continue the age distribution example, in 2020 the scenario that produces the maximum inventory is about 25% above the reference case and the scenario that produces the minimum inventory is about 25% below the reference case.

Across all pollutants, the range of emission results for the age distribution scenarios decreases substantially over time. Age distribution has a greater impact on cumulative emissions inventories for 2020 through 2040 compared with later future years (post-2040), reflective of the impact of near-term regulatory actions, such as SAFE Rule, HD GHG Phase 2 Rule, and Tier 3 Program. These results for future years can be attributed to older model year vehicles that do not comply with regulatory actions being

[7] Note that details on the maximum and minimum emissions inventory for each input and pollutant may be viewed by using the FHWA MOVES3 Sensitivity Dashboard. [6]

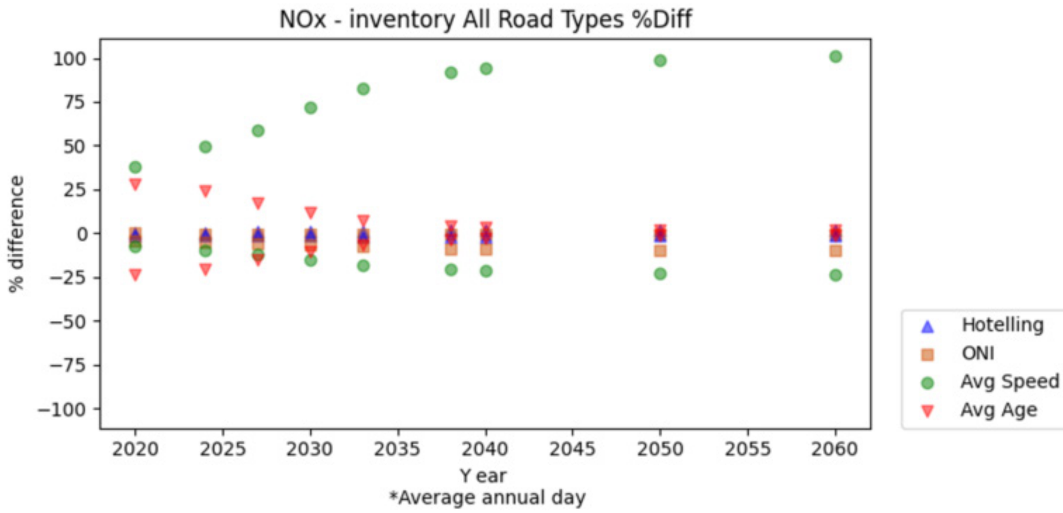
[8] $PM_{2.5}$ includes $PM_{2.5}$ exhaust (pollutantID 110), $PM_{2.5}$ brake wear (116) and $PM_{2.5}$ tire wear (117). Likewise, PM_{10} includes PM_{10} exhaust (100), PM_{10} brake wear (106) and PM_{10} tire wear (107)

removed from (or becoming a *de minimis* component of) the overall county fleet, and newer vehicles meeting stricter federal emissions standards becoming a larger portion of the fleet. It should be noted that the age distribution groupings used for this sensitivity analysis were intended to assess the sensitivity to changes in vehicle emissions over the entire lifespan available in MOVES, instead of the sensitivity to short term aging effects. Further analyses may yield different results if age distribution modifications are focused on the vehicles zero to ten years old rather than on the entire range of ages in MOVES.

Average speed distribution shows the opposite trend, generally increasing in sensitivity further into the future across all pollutants, but most significantly for NO_x and $PM_{2.5}$ (note the percent difference plots). Further into the future, the absolute impact of speed distributions are relatively constant and hence the range of inventories is relatively constant. In contrast, the reference inventory decreases in later out-years (especially for NO_x and $PM_{2.5}$), and hence the relative importance of speed distributions (the percent difference between the speed distributions inventories and reference scenarios) increases.

In comparison to average speed and age distribution, total inventories show significantly less sensitivity to hotelling and ONI activity. Hotelling is only applicable to combination long-haul trucks (source type 62), while the cumulative inventories include an aggregate of all vehicle types, resulting in small percent differences from the reference case in these scenarios. Similarly, ONI impacts only the off-network road type, with the aggregation across all road types resulting in minimal sensitivity for the entire emissions inventory. A noted exception is ONI's impact on NO_x and CO_2eq. Here ONI has a moderate impact on the total inventory with a slight increase in sensitivity in the further out years (i.e., 2040 and beyond). This increased sensitivity in future years is most likely due to a subtle interplay between ONI, VMT, and vehicle emission rates as they change in future years (see discussion in the section Off-Network, Unrestricted, and Restricted Road Types for more details).

Figure 1. NO_x Inventory Total



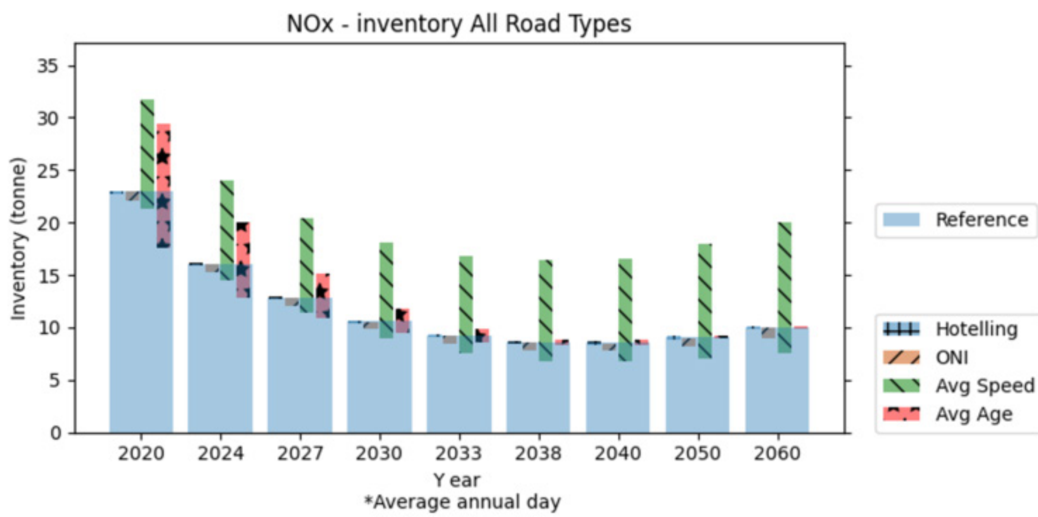


Figure 2. NO_x Inventory Total – Age distribution scenarios

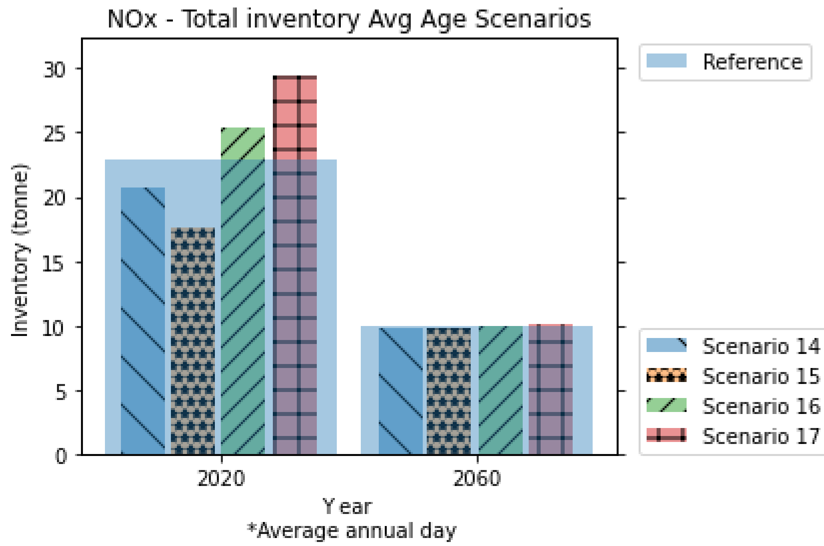
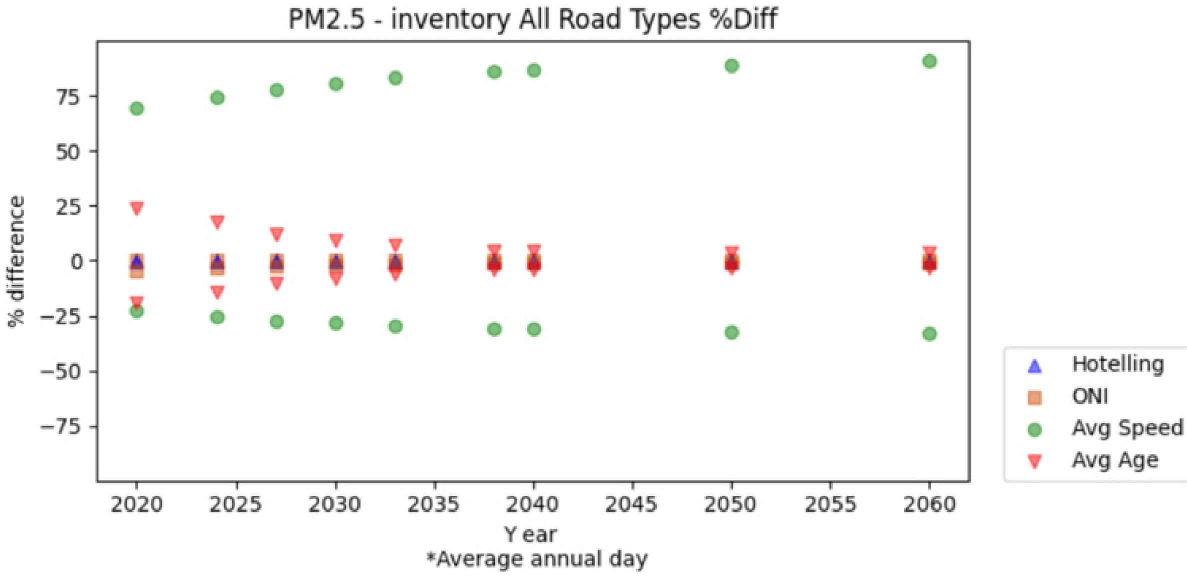


Figure 3. PM2.5 Inventory Total



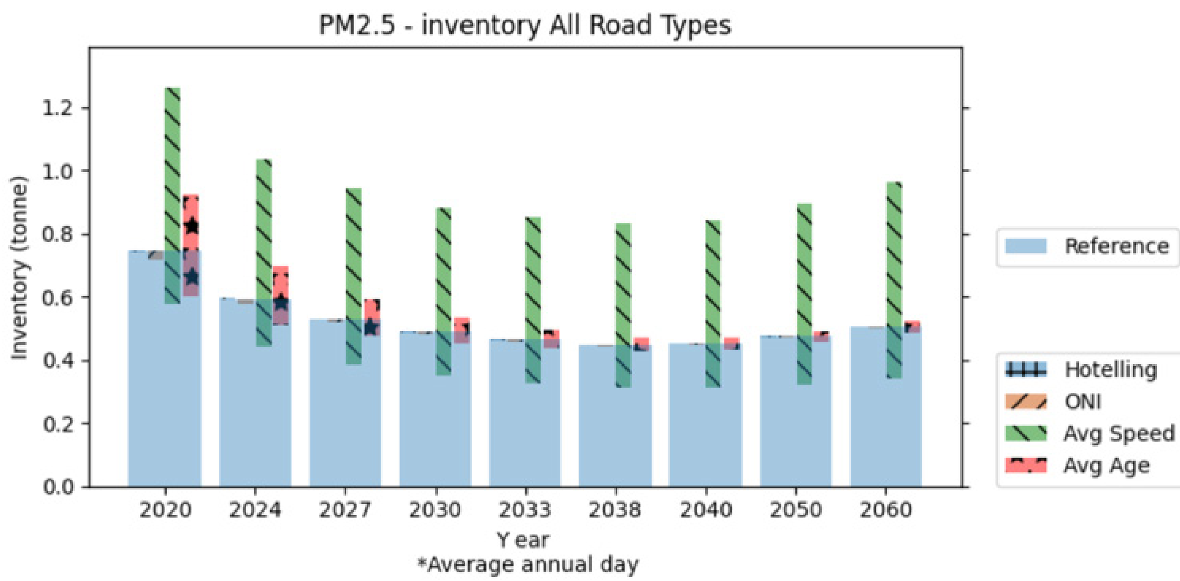
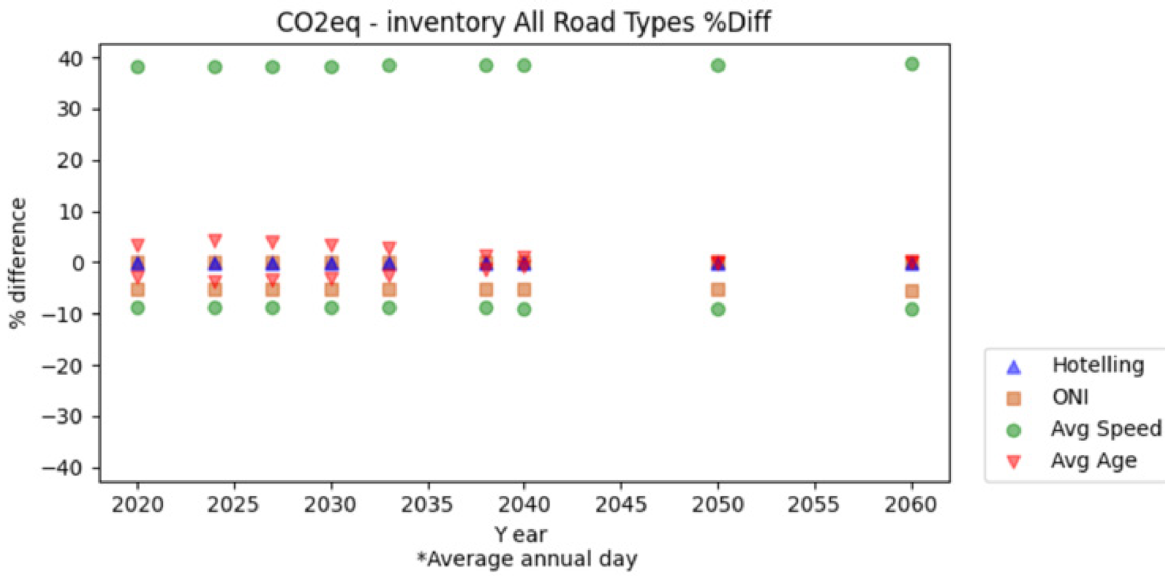
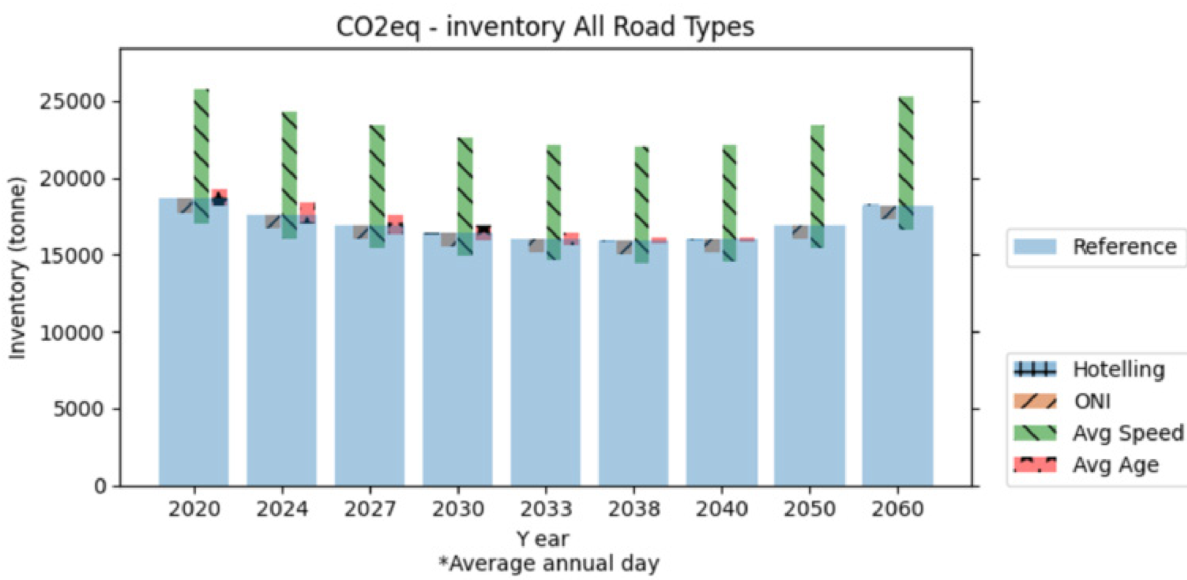


Figure 4. CO2eq Inventory Total





Appendix E – Complete Inventory Sensitivity Results contains the full set of plots for the following pollutants: CO, CO_2eq, NO_x, $PM_{2.5}$, PM_{10}, and VOC. The following subsections describe in greater detail the impact of the scenarios on specific subsets of the inventory that may be of interest to modeling stakeholders.

Light-Duty and Heavy-Duty Vehicles

This section examines a subset of the emissions inventories focusing on specific types of vehicles modeled in MOVES. Inventories are broken down into light-duty and heavy-duty emissions. Light-duty vehicle inventories include inventories aggregated across the county (including all road types and relevant processes) from the following source types:

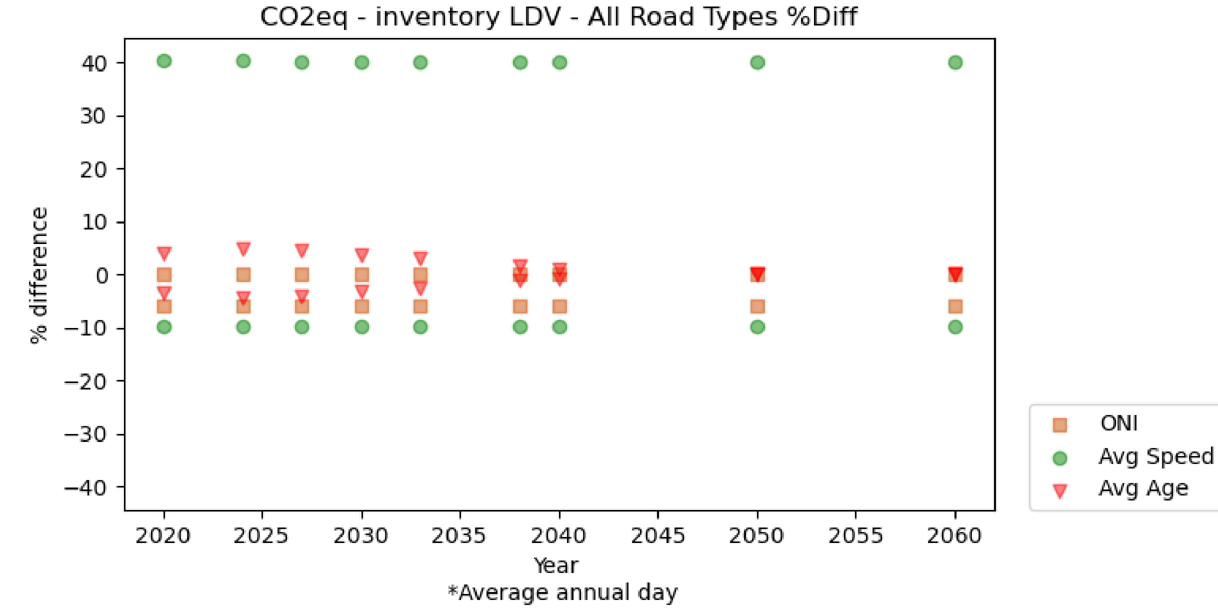
- motorcycles (11),
- passenger cars (21),
- passenger trucks (31), and
- light commercial trucks (32).

Heavy-duty vehicle inventories include inventories aggregated across the county (including all road types and relevant processes) of the following source types:

- the three types of buses (source types 41, 42, and 43),
- refuse trucks (51),
- single unit short-haul trucks (52),
- single unit long-haul trucks (53),
- motor homes (54),
- combination short-haul trucks (61), and
- combination long-haul trucks (62).

Figure 5 and Figure 6 show a comparison between reference cases and scenario groups for light-duty vehicles and for heavy-duty vehicles for CO_2eq inventories. Like the total inventory trends, most of the scenario groupings for light-duty vehicles (LDV) and heavy-duty vehicles (HDV) display decreasing emissions in later years, except for average speed scenarios, which decrease slightly between 2020 and 2040, but increase in later years. This decrease in cumulative emissions is most likely due to MOVES projecting decreases in older vehicle usage in near-term future years, leading to a reduction in CO_2eq emissions. In the more distant future, however, MOVES projects overall increases in total VMT for both light-duty and heavy-duty vehicles, with vehicle age distributions having less of an effect. Light-duty vehicles show different trends from heavy-duty vehicles in inventory totals for all pollutants when looking from year to year due to projected changes in emission rates for future model years for each vehicle type. Because hotelling is only relevant for long-haul combination trucks (source type 62), the hotelling scenarios, which have zero impact on light-duty vehicles, are omitted from the light-duty plots displayed below.

Figure 5. CO_2eq Light-Duty Vehicles Inventory



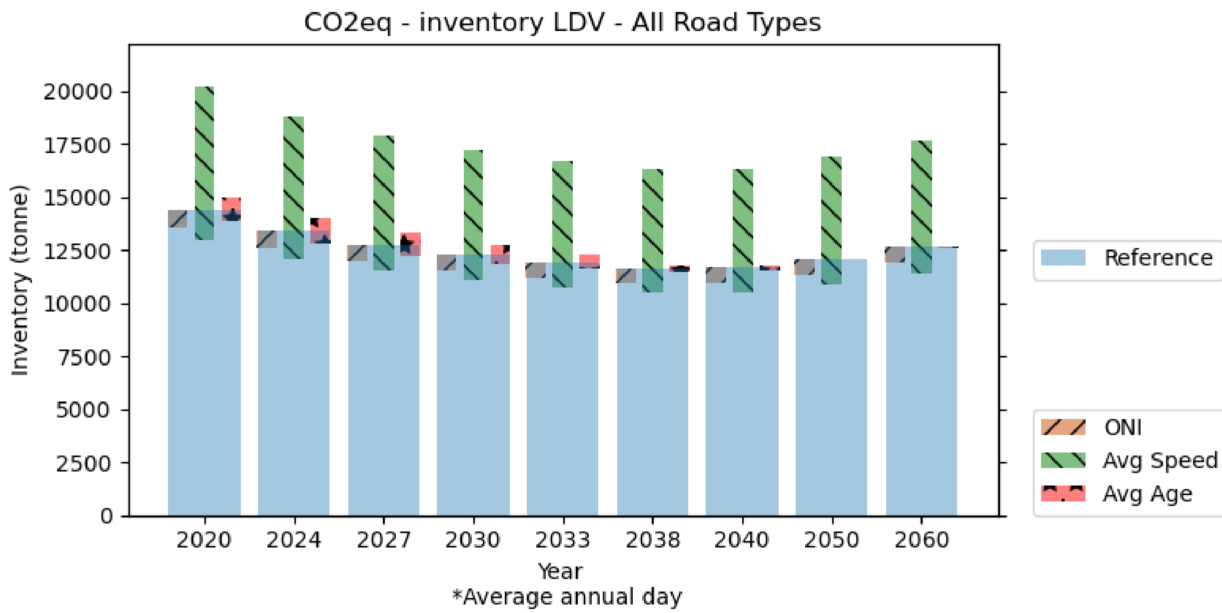
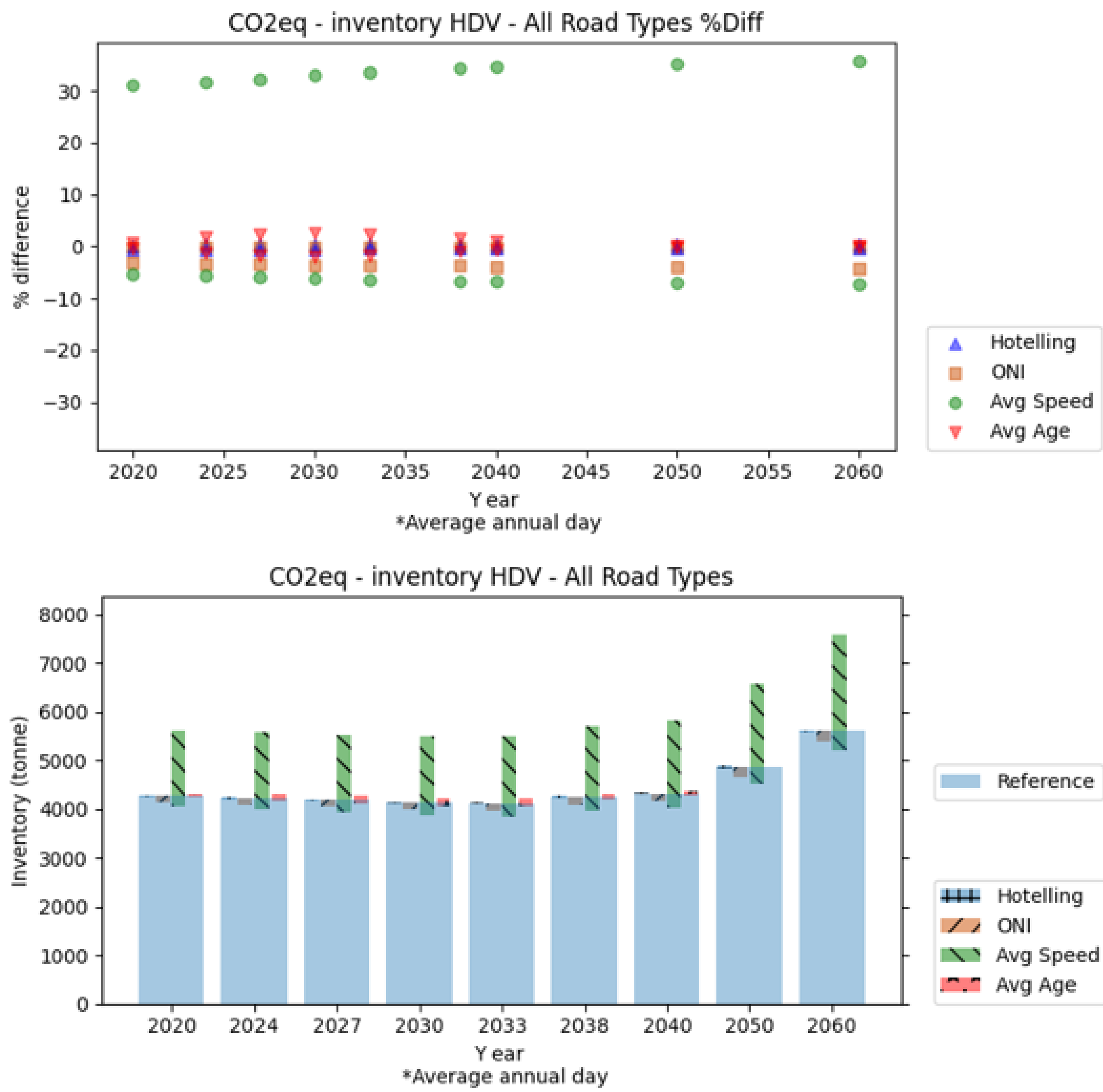


Figure 6. CO_2eq Heavy-Duty Vehicles Inventory



As in the total inventories, both light- and heavy-duty inventories show that average speed, age distributions, and ONI have the greatest impact on CO_2eq inventories. LDV CO_2eq inventories show a slightly greater sensitivity to speed distributions than HDV results in terms of percent differences, about 10% higher overall. Note the reference case had specific speed distributions for each vehicle type, the scenarios used the same speed distributions for all vehicle types, which may contribute to these differences in sensitivity across the source type categories.

For NO_x, there is a marked difference in the sensitivity of the scenarios for LDV versus the total inventory. Age distribution has the most substantial impact in the early years for LDV (through at least 2038), while average speed has the greatest impact in the later years. For HDV, NO_x has the highest sensitivity to average speed for all the years with an increasing sensitivity from 2020 through 2040, and a consistently greater sensitivity than LDV (see Figure 7 and Figure 8, respectively). This is due to substantially higher NO_x emissions in heavy-duty diesel vehicles and updated emission rates for low speed (see discussion below).

Figure 7. NO_x Light-Duty Vehicles Inventory

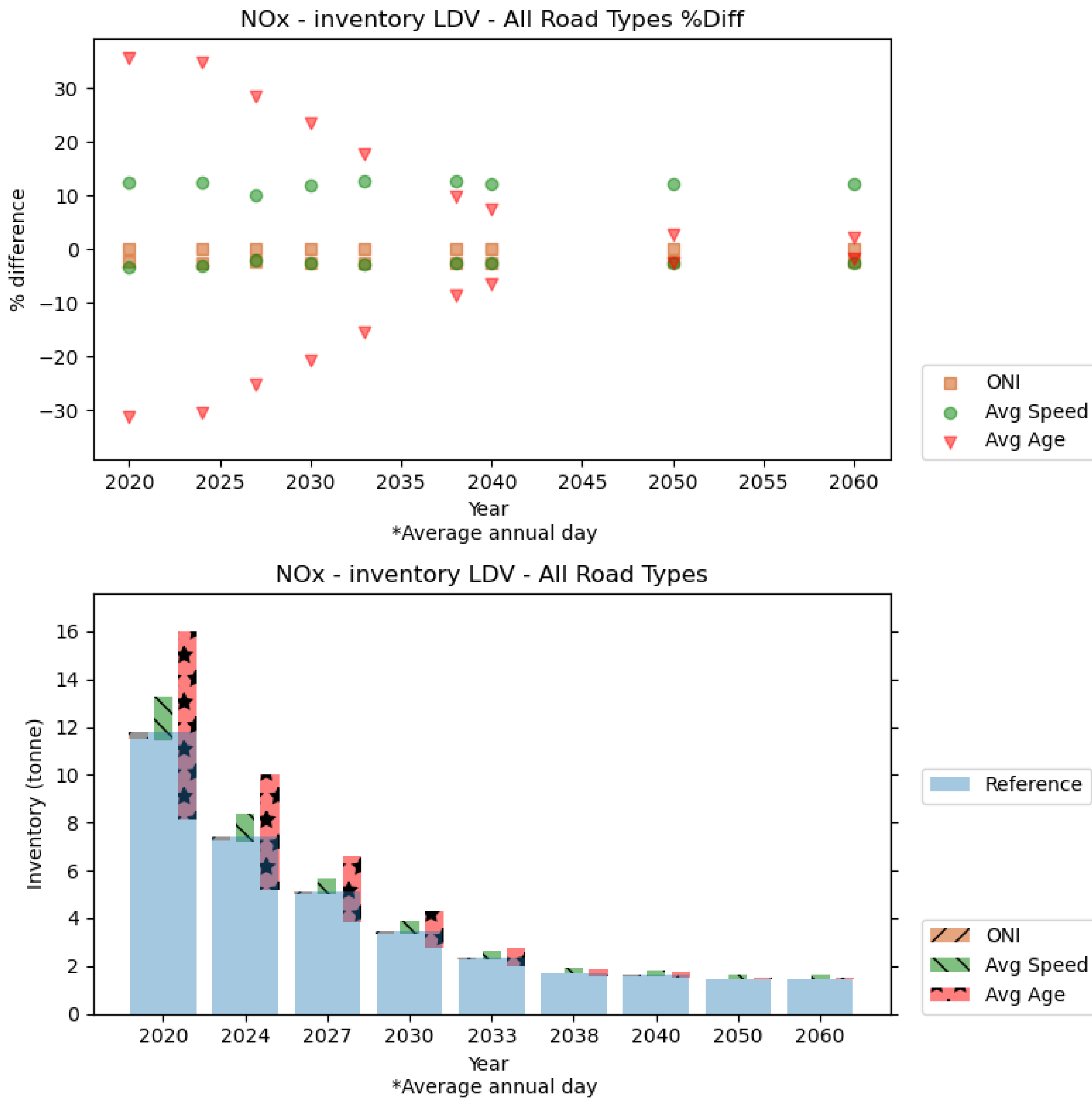
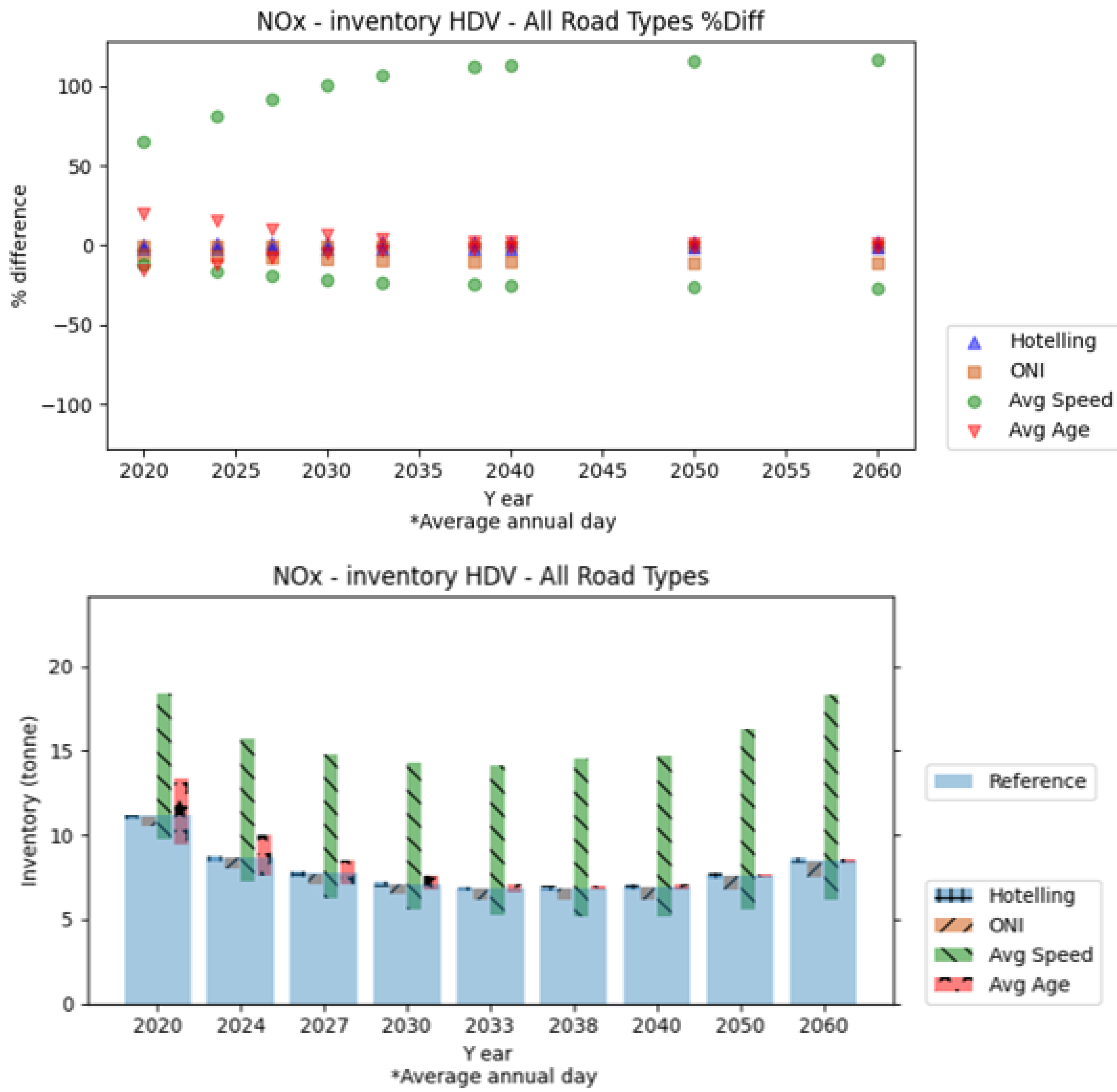


Figure 8. NO_x Heavy-Duty Vehicles Inventory



For $PM_{2.5}$ (refer to Figure 9 and Figure 10, respectively), HDV has a greater sensitivity to average speed than LDV, especially in the future years, which is due to a relatively constant impact of change in average speed with an overall decrease in the reference emissions for further out future years. HDV has a greater sensitivity to age distribution than LDV, especially in the baseline and near future years.

The ONI distributions had minimal impacts on inventories, as there is only a small percent difference between the inventories in these scenarios and the reference case (see Figure 5 through Figure 10). The exception is that ONI scenarios 5 through 10 do show a moderate impact on LDV inventory for CO_2eq and moderate impact on HDV inventories for NO_x. As in the total inventories, these plots show inventories for many types of vehicles and activity types. As such, Figure 5 through Figure 10 show that the ONI inputs only impact certain small subsets of the vehicles and their emissions-producing activities. For heavy-duty vehicles, hotelling also has a minimal impact on the inventory, as hotelling only effects a subset of heavy-duty vehicles (e.g., long-haul combination trucks only off-network). Thus, it can be expected that changes to these light-duty and heavy-duty inventories will be small for scenarios 1 through 4 as well as 5 through 10.

Figure 9. $PM_{2.5}$ Light-Duty Vehicles Inventory

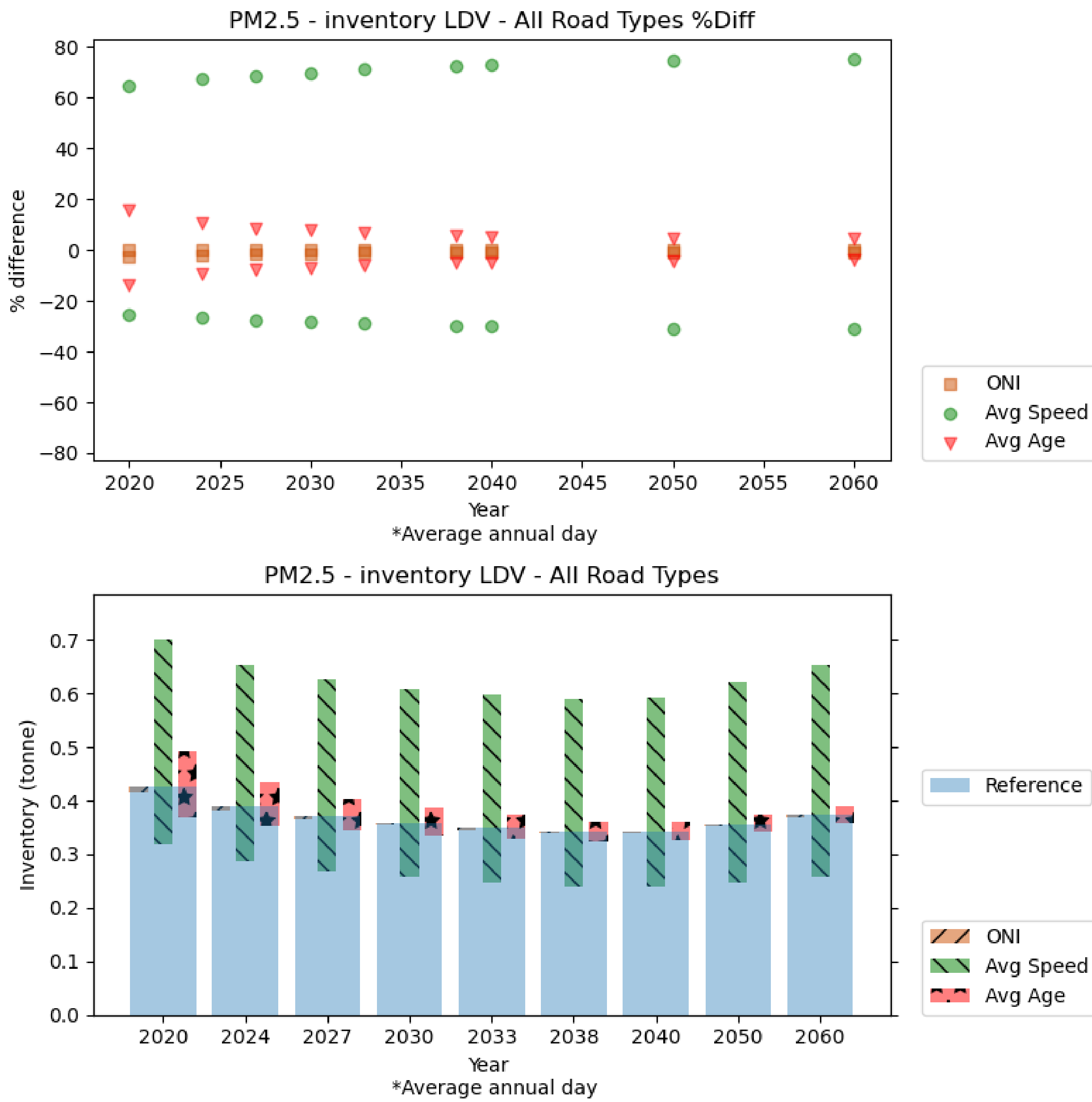
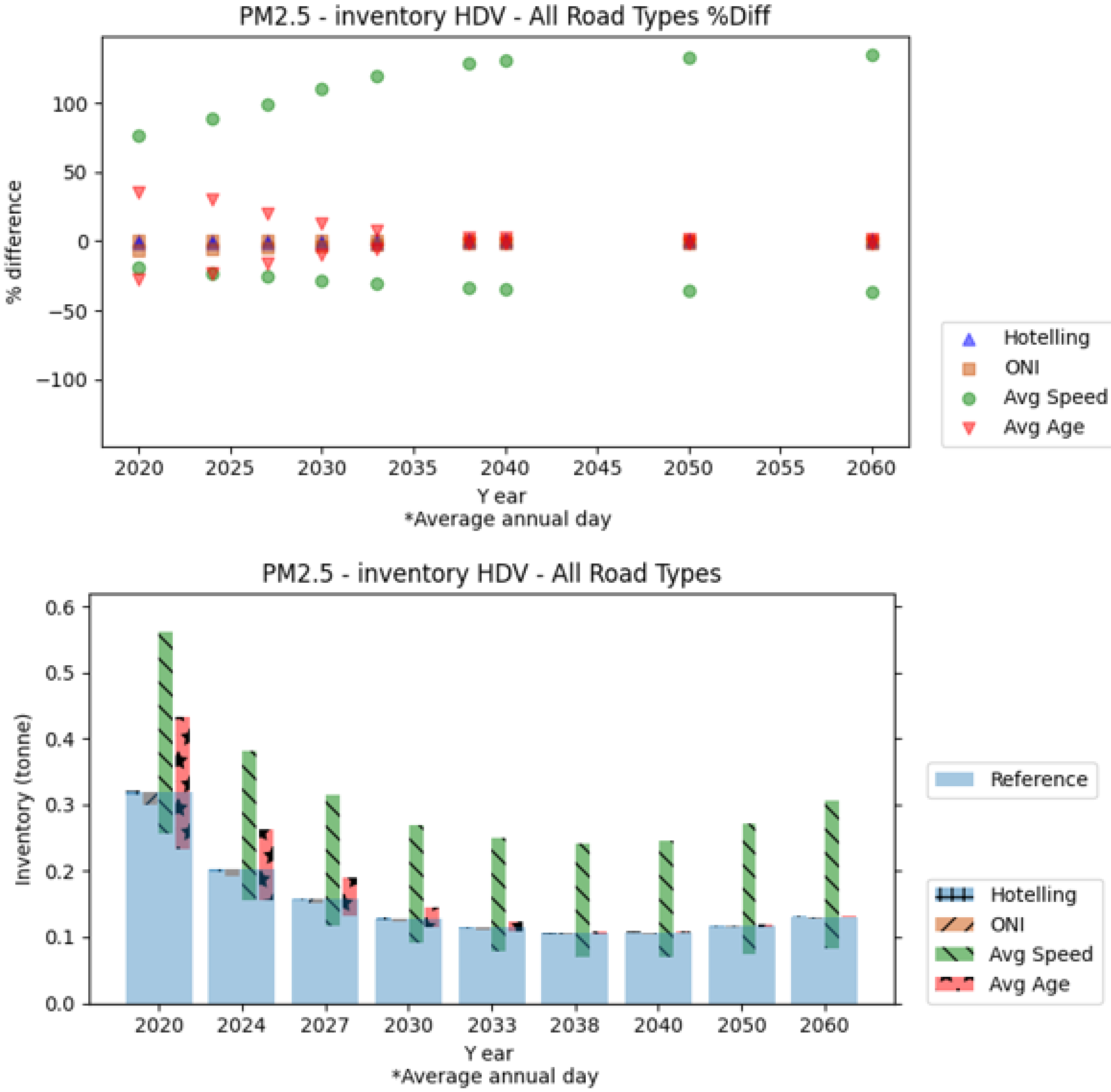


Figure 10. $PM_{2.5}$ Heavy-Duty Vehicles Inventory



Looking more closely at the long-haul combination trucks (source type 62), when heavy-duty vehicles spend more time travelling at lower speeds, they produce more NO_x (see Figure 11). Figure 12[9] shows that when speed distributions covering LOS F are applied (scenario 11F), vehicles spend more time in speed bins 1 through 9 than other speed distributions. MOVES3 has updated running rates for heavy heavy-duty (HHD) diesel that are meant to represent less effective NO_x controls during idle, low speeds, and low power operations. Therefore, under higher congestion conditions (e.g., FC 11 LOS F) modelers should expect higher NO_x emissions for these vehicle types. The same concept is true for any speed distribution that contains higher contributions from lower speed bins, as shown by the increase in NO_x inventory as the level of service in the scenarios shown in Figure 11 goes from LOS B to LOS F (generally,

[9] For plots of speed distribution used in other scenarios, see Appendix B – Scenario Development.

fastest to slowest). Thus, the NO_x inventories for these vehicle types are more sensitive to average speed distribution inputs than other pollutants.

Figure 11. Long-haul Combination Trucks Inventory of Specific Average Speed Distributions

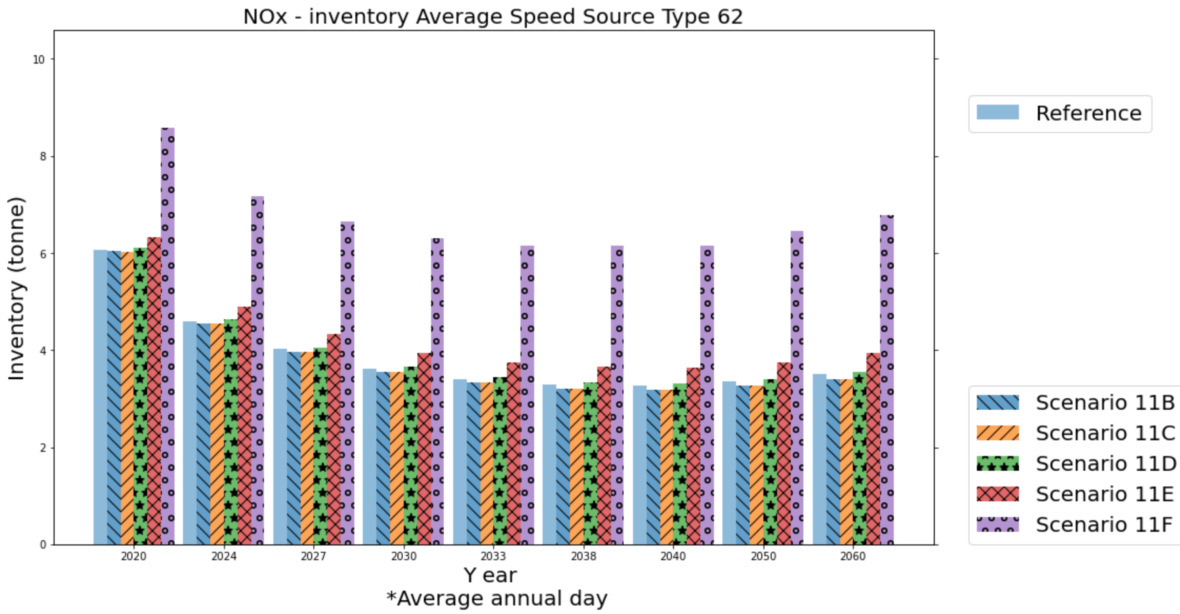
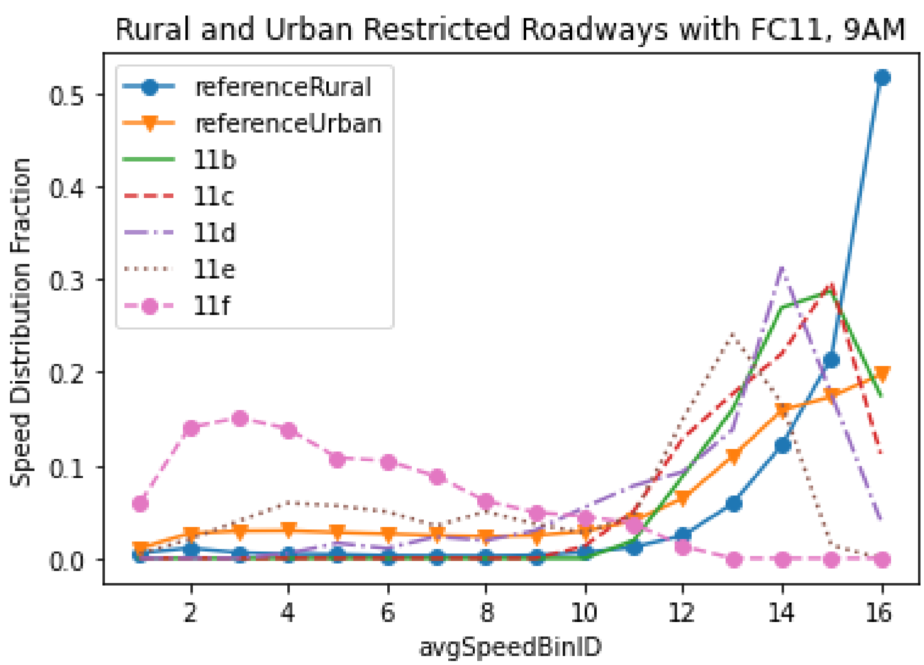


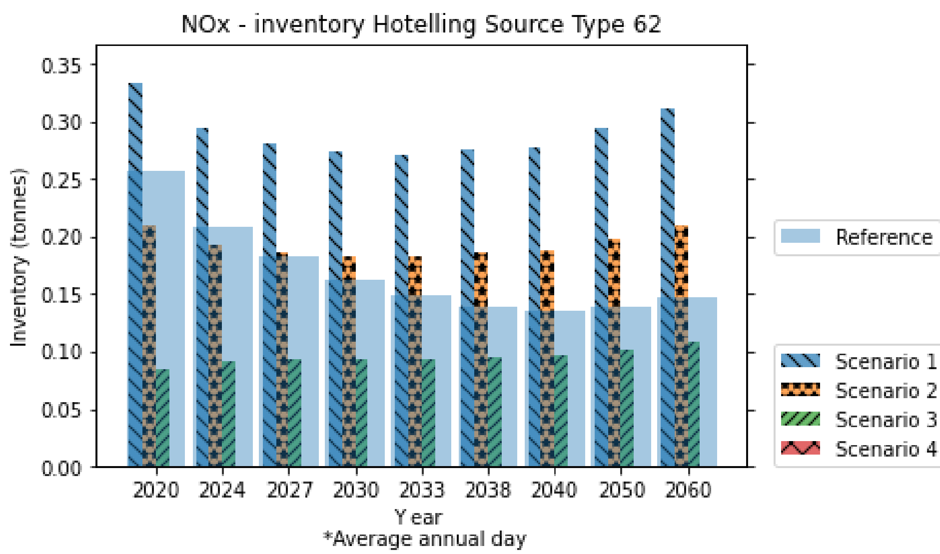
Figure 12. Urban and Rural Restricted Roadway Average Speed Distributions (Scenario 11)



Long-haul combination trucks (sourcetype 62) are the only source type that has hotelling activity and hence hotelling emissions (see Figure 13 and Figure 14). This sensitivity analysis utilized the default method of calculating hotelling hours. Based on MOVES technical reports published by EPA, MOVES calculates hotelling based on the total VMT driven by sourcetype 62 vehicles on urban and rural restricted roadways (highways)[10] [5]. In default mode, MOVES multiplies this VMT by a factor of 0.0072 to obtain the number of total hotelling hours for the fleet, which is then distributed to the different types of hotelling (e.g., extended idle, diesel or battery APU, and engine off). These hotelling type distributions were modified for the scenarios studying hotelling inputs in Scenarios 1 through 4.

The default hotelling type distributions were used in the reference case inputs. Thus, when examining hotelling on its own, the scenarios are expected to be above and below the reference case. The trends in Figure 13 align with trends in emission rates associated with the different type of hotelling: Scenario 1 shows the greatest inventory due to the 100% extended idle rate in that scenario; Scenarios 2 and 3 have varying shares of diesel or battery APU idling types, and thus produce slightly lower inventories in these cases; Scenario 4 has 100% usage of "all-off" idling, modelling a truck stop electrification scenario or battery APU (i.e., zero hotelling emissions). Interestingly, Scenario 2 produces a lower inventory than the reference case in year 2020 but is higher than the reference in years 2030 and later. This is due to the reference in the further out years having a lower percentage of extended idle than Scenario 2.

Figure 13. NO_x Hotelling Scenarios



[10] In MOVES2014 only rural restricted VMT from long-haul combination trucks (62) was used to calculate default hotelling hours.

Figure 14. CO_2eq Hotelling Scenarios

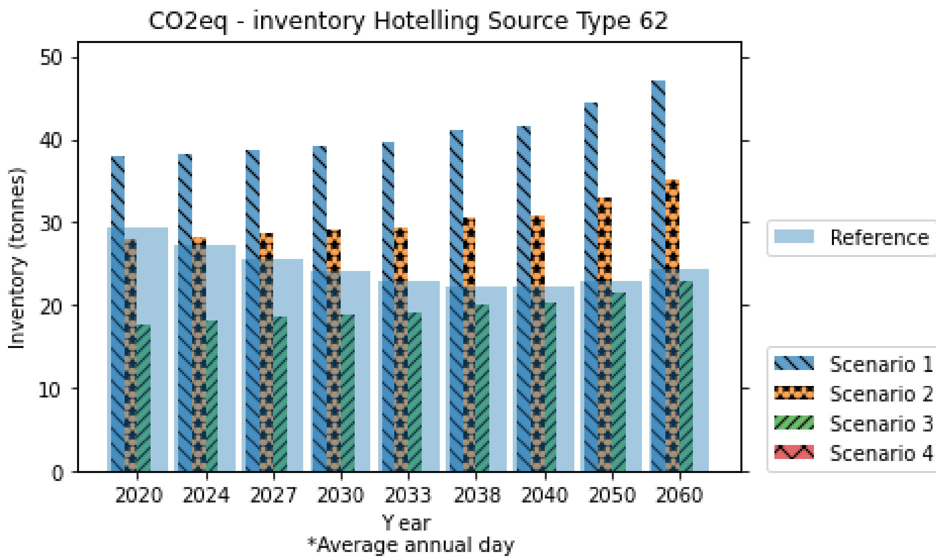
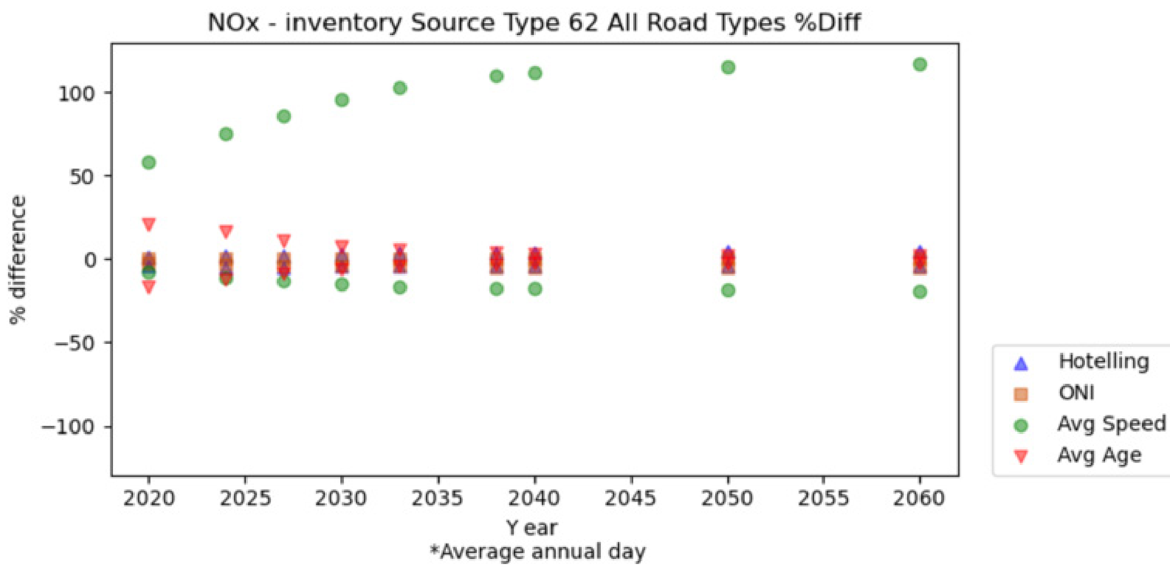


Figure 15 and Figure 16 show the percent difference in the hotelling scenario inventories for source type 62 in the context of all the scenario groupings for NO_x and CO_2eq, respectively, in contrast to Figure 8 and Figure 9, which show the NO_x and CO_2eq inventories for all heavy-duty vehicles. The inventories in Figure 15 and Figure 16 include emissions from running and starts in addition to hotelling, thus leading to a larger inventory across all scenarios than in Figure 13 and Figure 14, which include only emissions from hotelling activities (e.g., extended idle, hotelling diesel APU, hotelling battery APU or TSE, and hotelling all engines off).

Figure 15. NO_x Source Type 62 Inventory



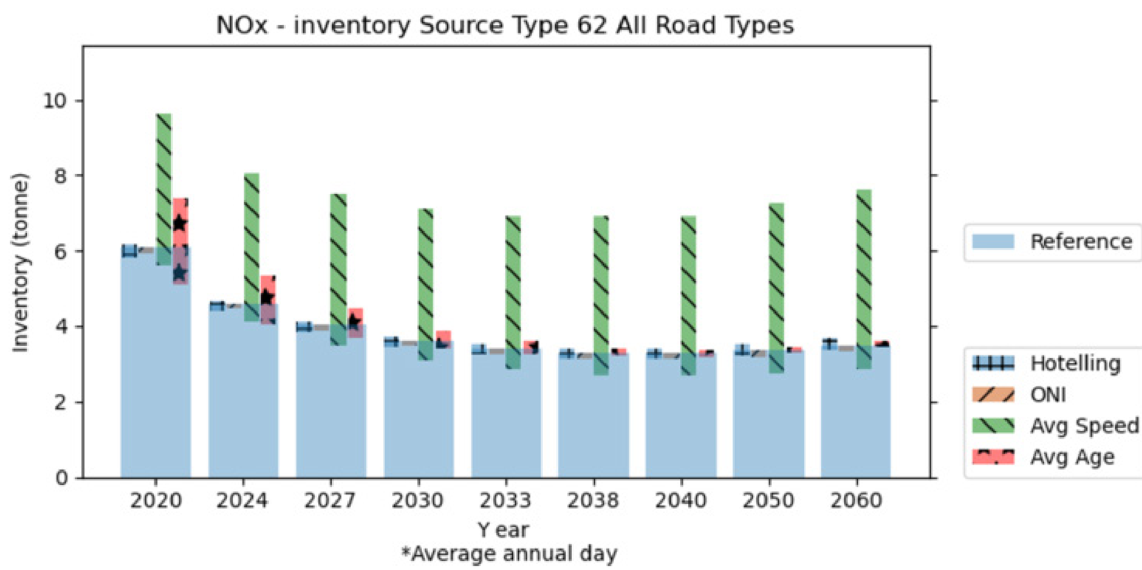
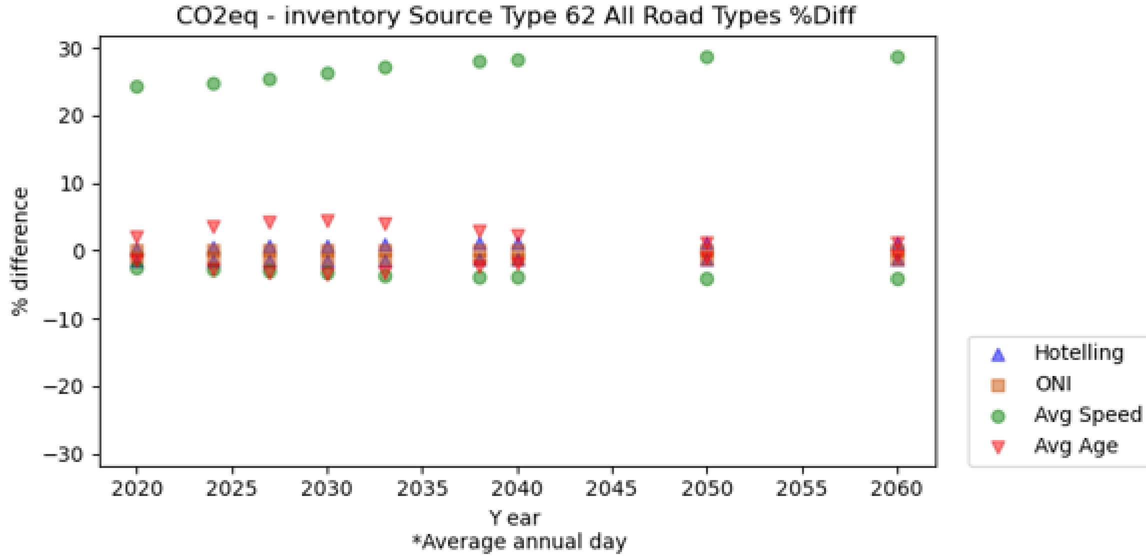
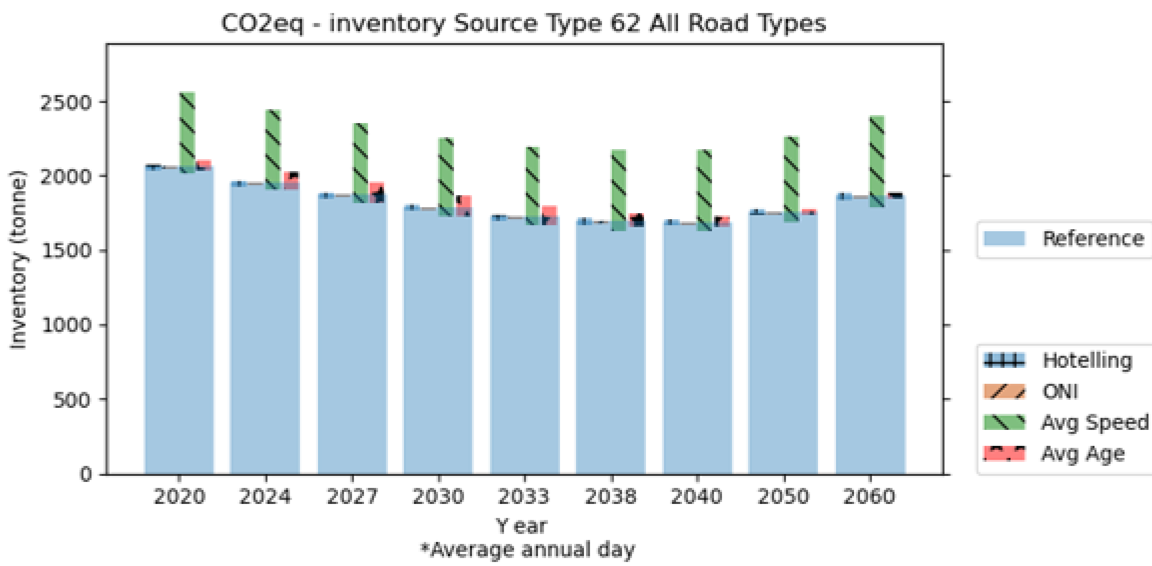


Figure 16. CO_2eq Source Type 62 Inventory



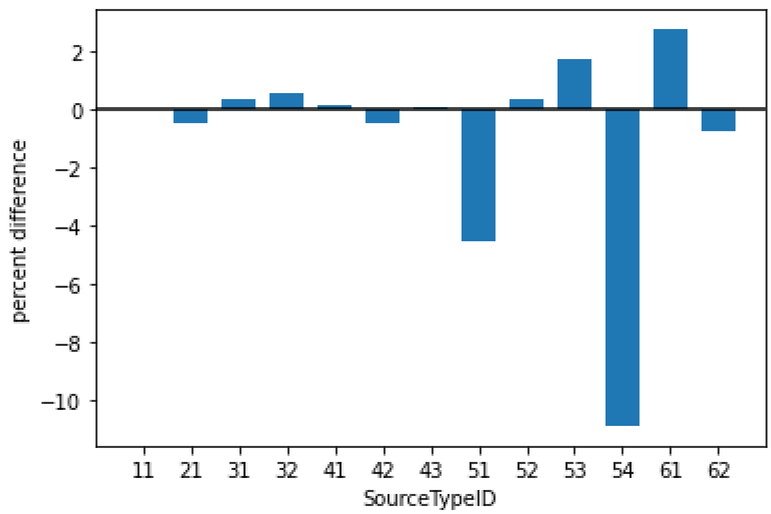


Unlike the other sensitivity cases, the age distribution scenarios do not preserve VMT at the source type level. Figure 17 shows the percent difference of VMT by source type between scenario 15 (significantly younger fleet) and the reference in 2020. This shift in VMT is due to a subtle interaction between relative mileage accumulation rates (RMAR) and age distribution when MOVES allocates VMT from Highway Performance Management System (HPMS) vehicle classification totals (typically input by a user) to source type totals. If the RMAR curves are significantly different within an HPMS class, for example for HPMS 50 (source types 51, 52, 53, and 54), then changes in age distribution may have a significant impact on how VMT is accumulated across these source types[11]. By aggregating VMT back up to the HPMS classes (10, 25, 40, 50, and 60), VMT will be preserved between the age distribution

[11] For more details on RMAR and the specific RMAR curves, see Section 6.2 of Population and Activity of Onroad Vehicles in MOVES3 (EPA-420-R-21-012, April 2021). [5]

scenarios and the reference runs[12]. Therefore, changes in age distribution have the potential for a compounding impact of changes in the total inventory and of a shift in activity and hence emissions when comparing inventories across different source types.

Figure 17. Age distribution impact on VMT and Source Type in Scenario 15



Off-Network, Unrestricted, and Restricted Road Types

In this section, specific inventories for some specific types of roadways have been highlighted. MOVES outputs are categorized based on the types of roadways on which the emissions were produced. These roadway types are broken up into urban and rural roadways, as well as restricted and unrestricted roadways. MOVES also includes an "Off-network" roadway for emissions that cannot be attributed specifically to the roadway network. This includes emissions from vehicles idling in parking lots or drive-throughs, start and crankcase start exhaust, as well as extended idle or auxiliary power emissions from heavy-duty long-haul trucks during hotelling hours. The off-network road type also includes evaporative emissions from parked vehicles. The 5 road types are:

- 1: Off-Network
- 2: Rural Restricted Access
- 3: Rural Unrestricted Access
- 4: Urban Restricted Access
- 5: Urban Unrestricted Access

The off-network inventory discussed in this section includes off-network road emissions (road type 1) aggregated across the county. Note that the off-network emissions inventory is much smaller compared to the on-network inventories, which consists of rural restricted access, rural unrestricted access, urban restricted access, and urban unrestricted access road types. The unrestricted inventory includes running and crankcase emissions, as well as some evaporative emissions, on unrestricted access rural and urban roads (road types 3 and 5, respectively) aggregated across the county. The restricted access inventory includes running and crankcase emissions, as well as some evaporative emissions, on restricted access

[12] Motorcycles (source type 11) show no change in VMT with a change in age distribution because there is only one source type and hence only one RMAR curve in the HPMS class 10.

rural and urban roads (road types 2 and 4, respectively) aggregated across the county. For a list of the specific types of MOVES emissions processes included in each inventory and road type group, see Appendix C, specifically Table 7.

Off-network Idle (ONI) has a significant impact on off-network emissions inventories for all pollutants since ONI only takes place outside of the drive cycle (e.g., idling during pick-up and drop-off of passengers and during deliveries). This idling contributes to total emissions but does not take place on the road network. MOVES3 models ONI as running emissions (process IDs 1 and 15) on the off-network road type (road type 1) as source hour operating (activity type 4). The ONI scenarios model various reductions in total idle fraction for various source types. These scenarios were intended to be representative of real-world idle reduction policy scenarios. The effects of these hypothetical policies on emissions are reflected in the reduction in emissions results shown in Figure 18, Figure 19, and Figure 20.

Off-network $PM_{2.5}$ emissions inventories are sensitive to changes in amount of off network idle activity in the region, particularly in years between 2020 and 2030 (see Figure 18). Unlike the total inventory trends, age distribution has a more sustained sensitivity across all modelled years. However, NO_x (see Figure 19) has the greatest sensitivity to ONI for further out future years, with percent differences from the reference ranging from approximately negative 25% to negative 40%. While CO_2eq (see Figure 20) has a more sustained sensitivity to ONI across all modelled years, with percent differences from the reference of approximately negative 60% for all years.

Figure 18. $PM_{2.5}$ Off-Network Inventory

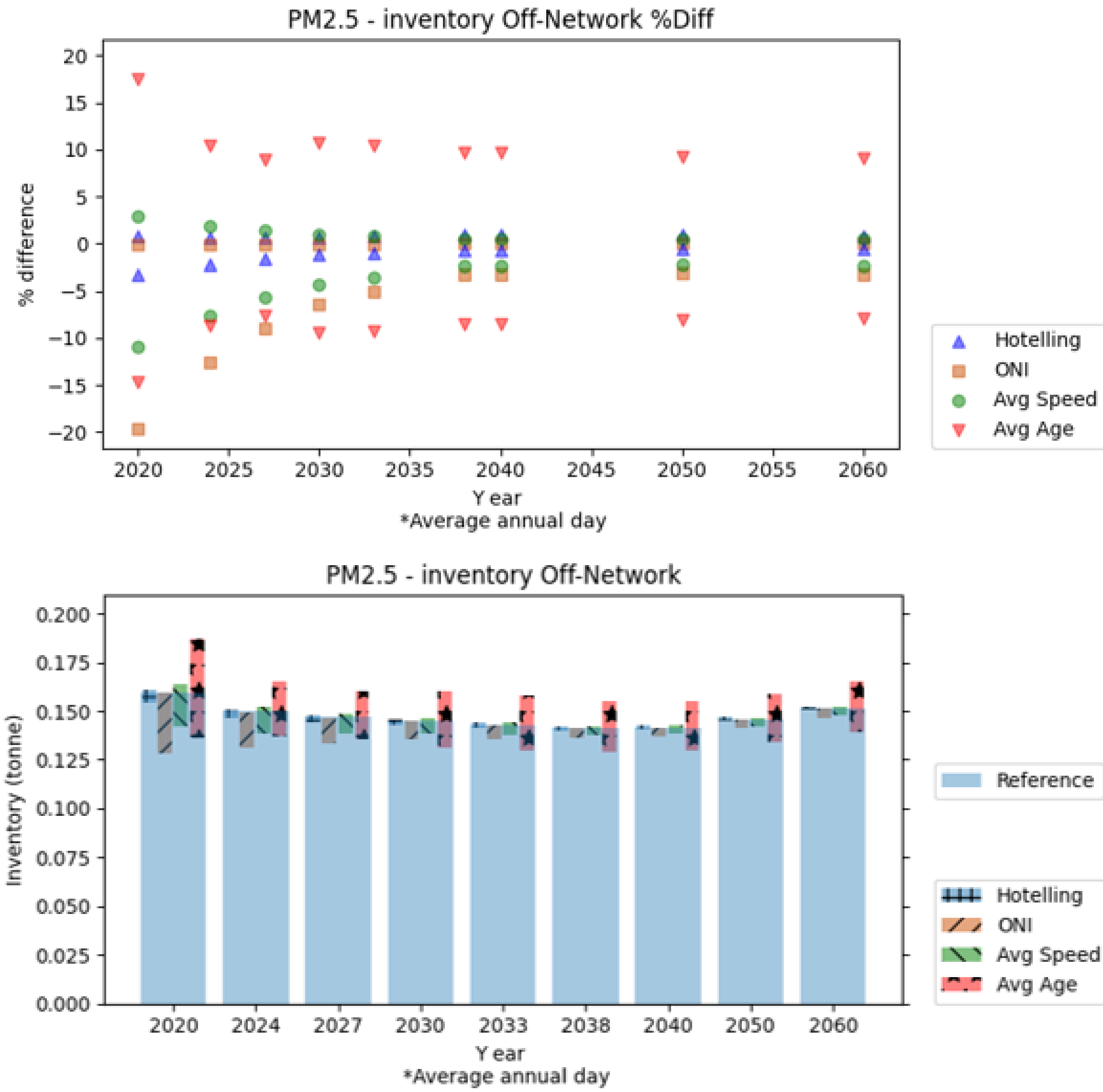
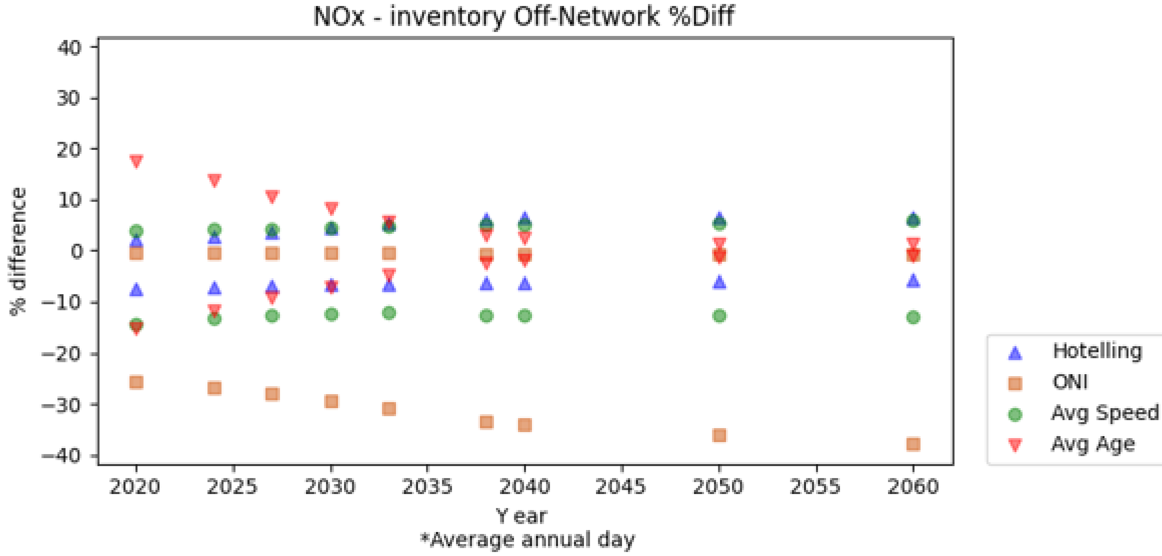


Figure 19. NO_x Off-Network Inventory



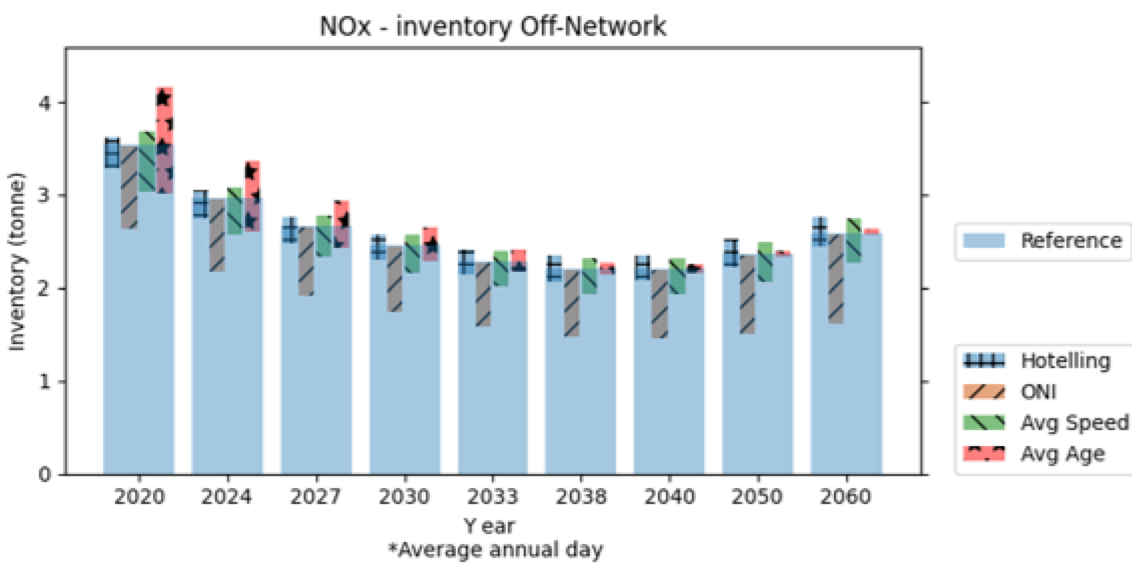
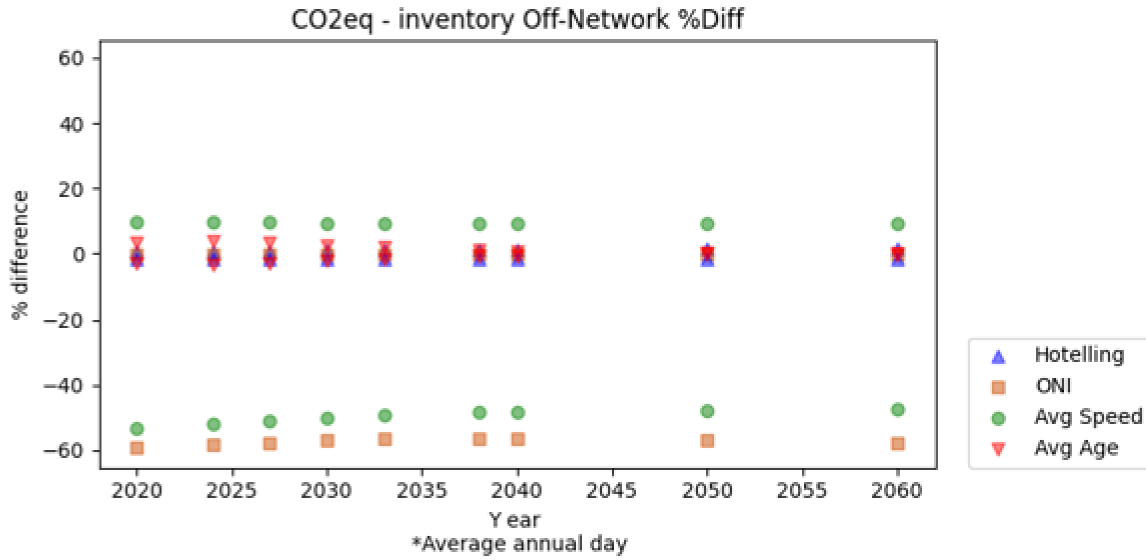
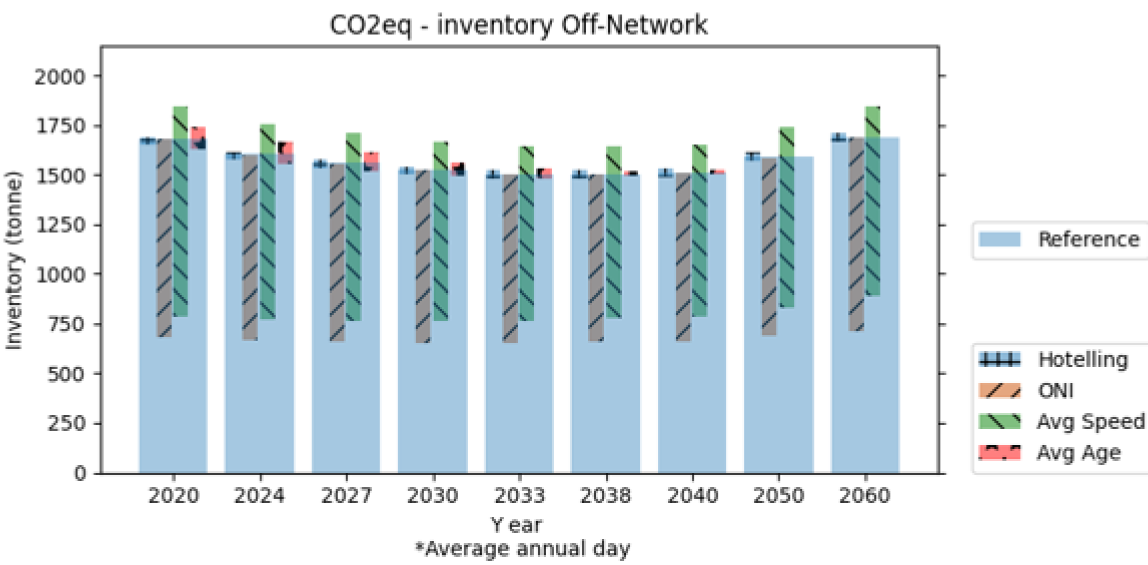


Figure 20. CO_2eq Off-Network Inventory





The off-network inventories for $PM_{2.5}$, NO_x, and especially CO_2eq (see Figure 18, Figure 19, and Figure 20) are sensitive to average speed distributions. Although this may seem counterintuitive, this sensitivity is due to the interrelationship between idle on-network and off-network. Average speed distributions affect how much time vehicles spend driving in the lowest speed bin, speed bin ID 1. This lowest speed bin (speeds less than 2.5 mph) includes some amount of time vehicles spend idling on on-network roadway types (road types 2 through 5 in MOVES). Thus, when the distribution in speed bin 1 changes, it also affects the amount of idle time on on-network roadways.

However, the total amount of time that vehicles spend idling on AND off the road network is accounted for in MOVES by a Total Percent Idling value that describes all idling (except extended idle for heavy-duty vehicles during hotelling), including off network idle (roadway type 1). In other words, this “Total Idle Fraction” (TIF) accounts for all time a vehicle spends idling inside and outside of normal drive cycles.

Because the total percent idle does not change in the speed distribution scenarios, and the on-network idling hours do change, the off-network idle hours must change to maintain the same total idle percentage. These effects may be better understood through the equation given in the MOVES on-road technical report, equation 10-5 on page 70 gives:

$$TIF = \frac{\left(\sum_{i=2}^{5} SHI_i\right) + ONI}{\left(\sum_{i=2}^{5} SHO_i\right) + ONI} \qquad (1)$$

Where:

$\sum_{i=2}^{5} SHI_i$ is the sum of all source hours idling on roadtypes 2 through 5

$\sum_{i=2}^{5} SHO_i$ is the sum of all source hours operating on roadtypes 2 though 5

ONI is the number of off-network idling hours

TIF is the total idle fraction. [5]

Both the total source hours idling (SHI) and the total source hours operating (SHO) in this equation are calculated using the total VMT by source type in the MOVES input database and the average speed distribution, so they can both change when the speed distribution changes. Thus, if the TIF stays constant as well, the ONI value in equation 1 above may change when the average speed distribution changes. These effects are illustrated specifically for ONI activity emissions inventories in Figure 21 and Figure 22, which compare the ONI CO_2eq inventory totals for the reference case and the different speed distributions of Scenario 11 and Scenario 13, respectively. The ONI inventory was found to increase slightly as the restricted roadways get more congested in Scenario 11[13]. This indicates that the rate of increase of SHO as a result of the changes in average speed distribution out-pace the rate of increase in SHI which results from the higher congestion, thus resulting in greater off network idle hours to maintain a constant total idle fraction. In contrast, the ONI inventory was found to decrease substantially in Scenario 13 as the unrestricted roadway congestion increases, indicating that the value of SHI increases faster than the total SHO as vehicles spend more time in the lowest speed bin. In this case ONI must decrease overall to maintain a constant total idle percentage.[14] For more information on how users should use the off-network idling input tables, see section 4.12 in EPA's MOVES3 Technical Guidance.[15] [1]

[13] Note Scenario 11B has the least congestion and 11F has the most congestion on urban and rural restricted road types.

[14] Note Scenario 13B has the least congestion and 13F has the most congestion on urban and rural unrestricted road types.

Figure 21. Scenario 11 Off-Network Idle Inventory – CO_2eq

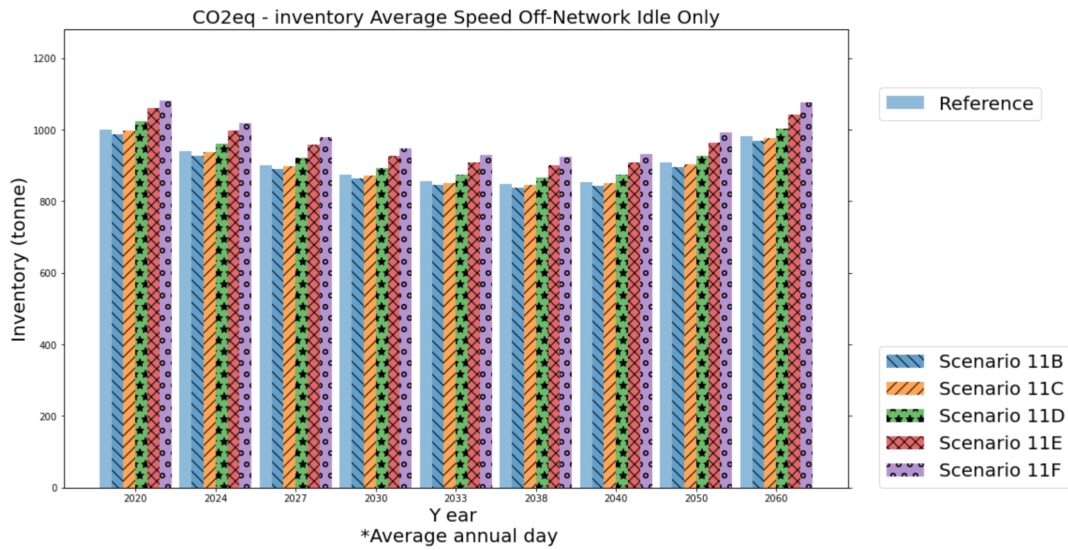
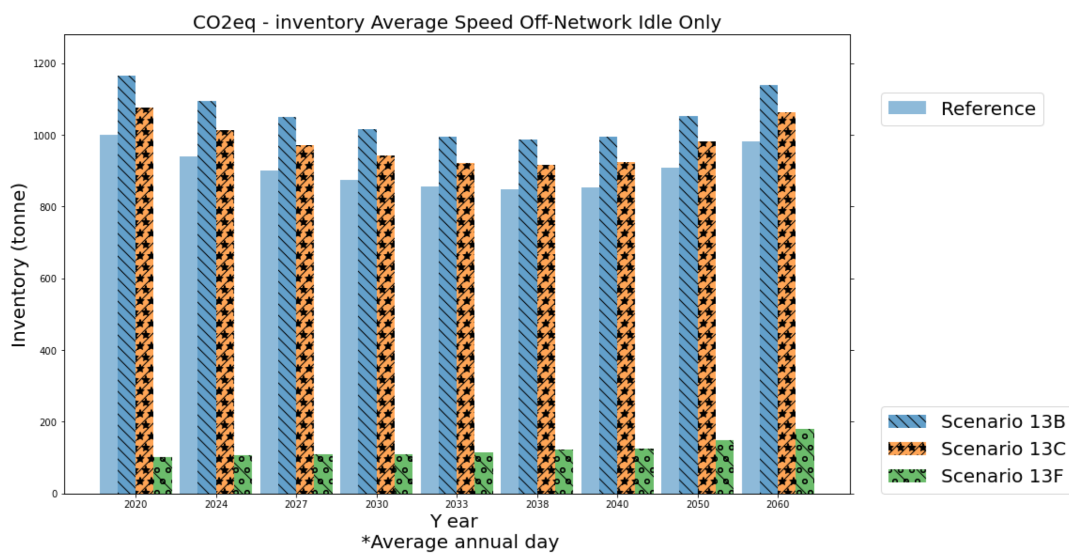
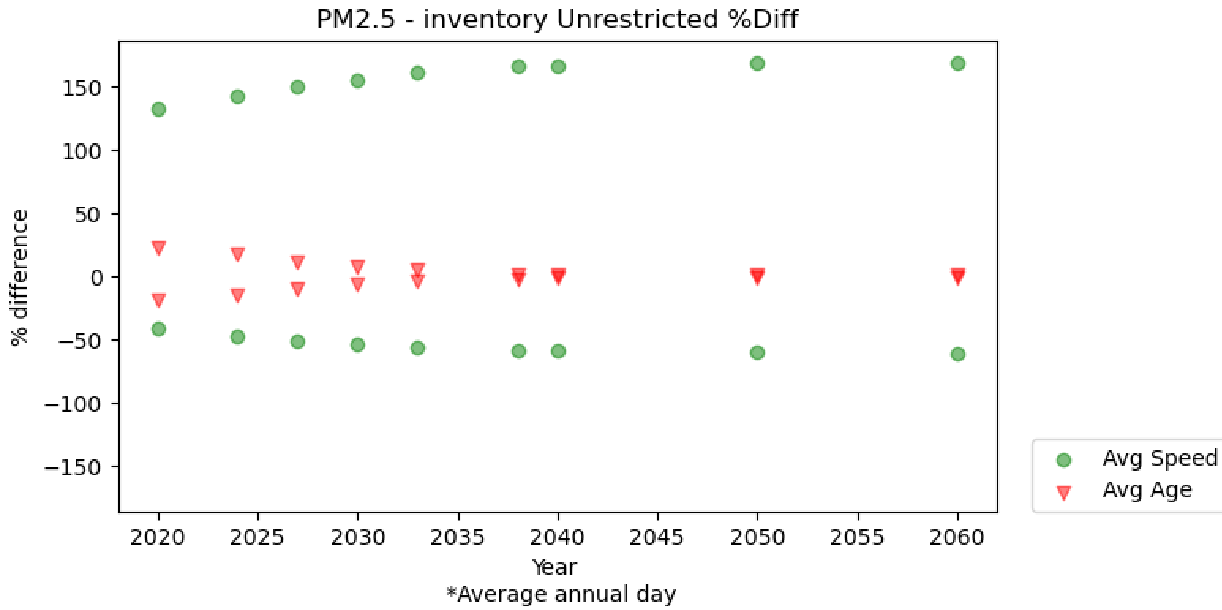


Figure 22. Scenario 13 Off-Network Idle Inventory – CO_2eq



Unrestricted access roads emissions results for all four inputs generally follow the same trends as the total inventory for $PM_{2.5}$ (Figure 23), NO_x (Figure 24), and CO_2eq (Figure 25), with average speed increasing in sensitivity in later years, and age distribution decreasing in sensitivity. Hotelling and ONI scenarios, which are relevant only for off-network road types, have no percent difference from the reference case and are thus omitted in Figure 23, Figure 24, and Figure 25.

Figure 23. $PM_{2.5}$ Unrestricted Access Roads Inventory



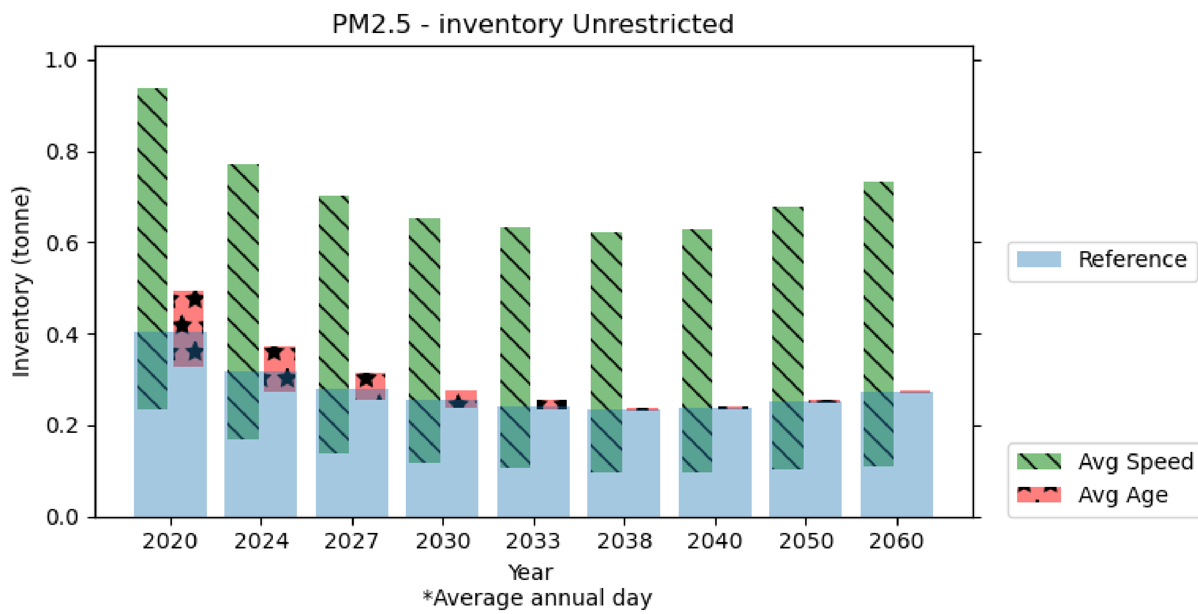


Figure 24. NO_x Unrestricted Access Roads Inventory

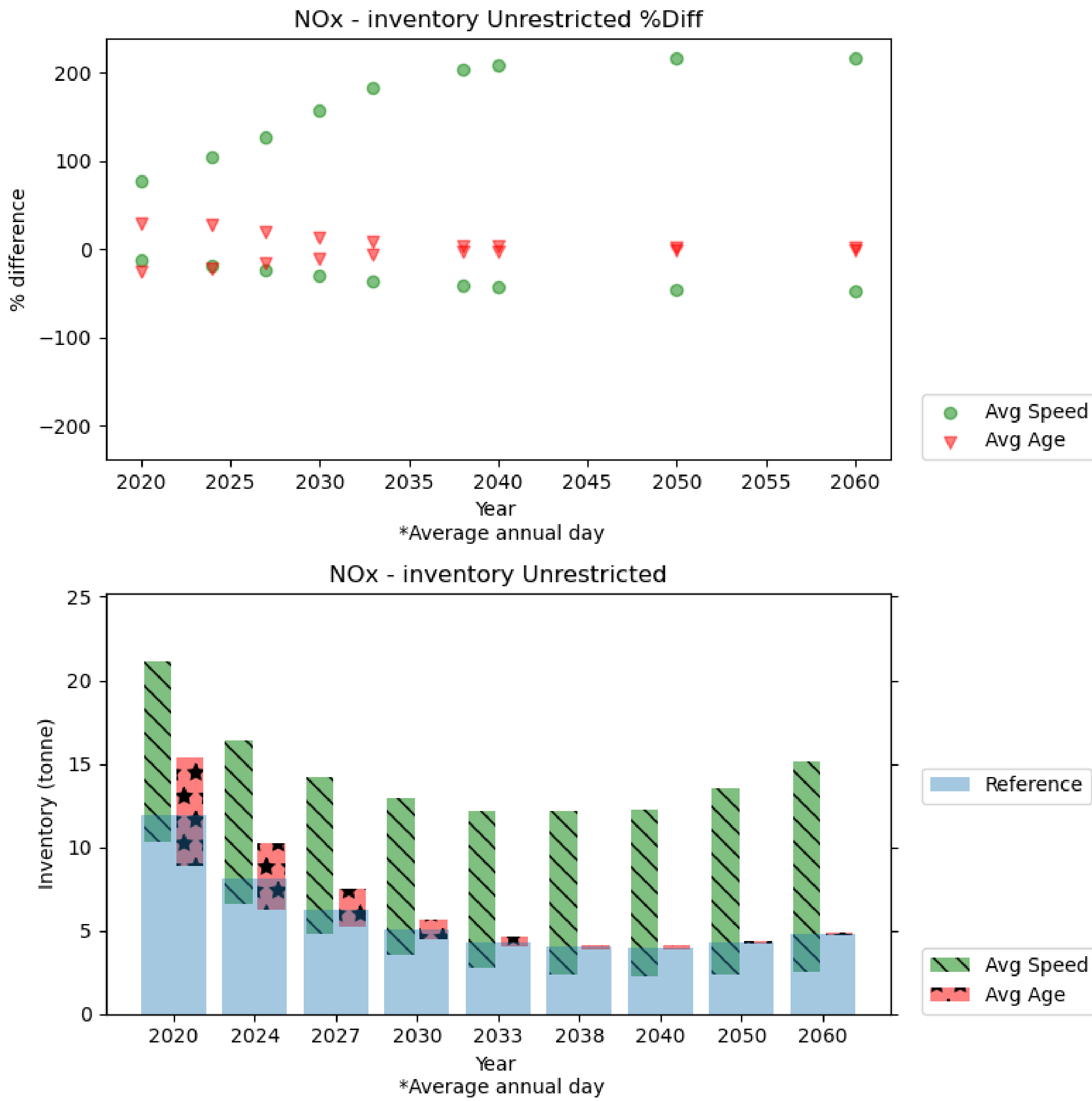
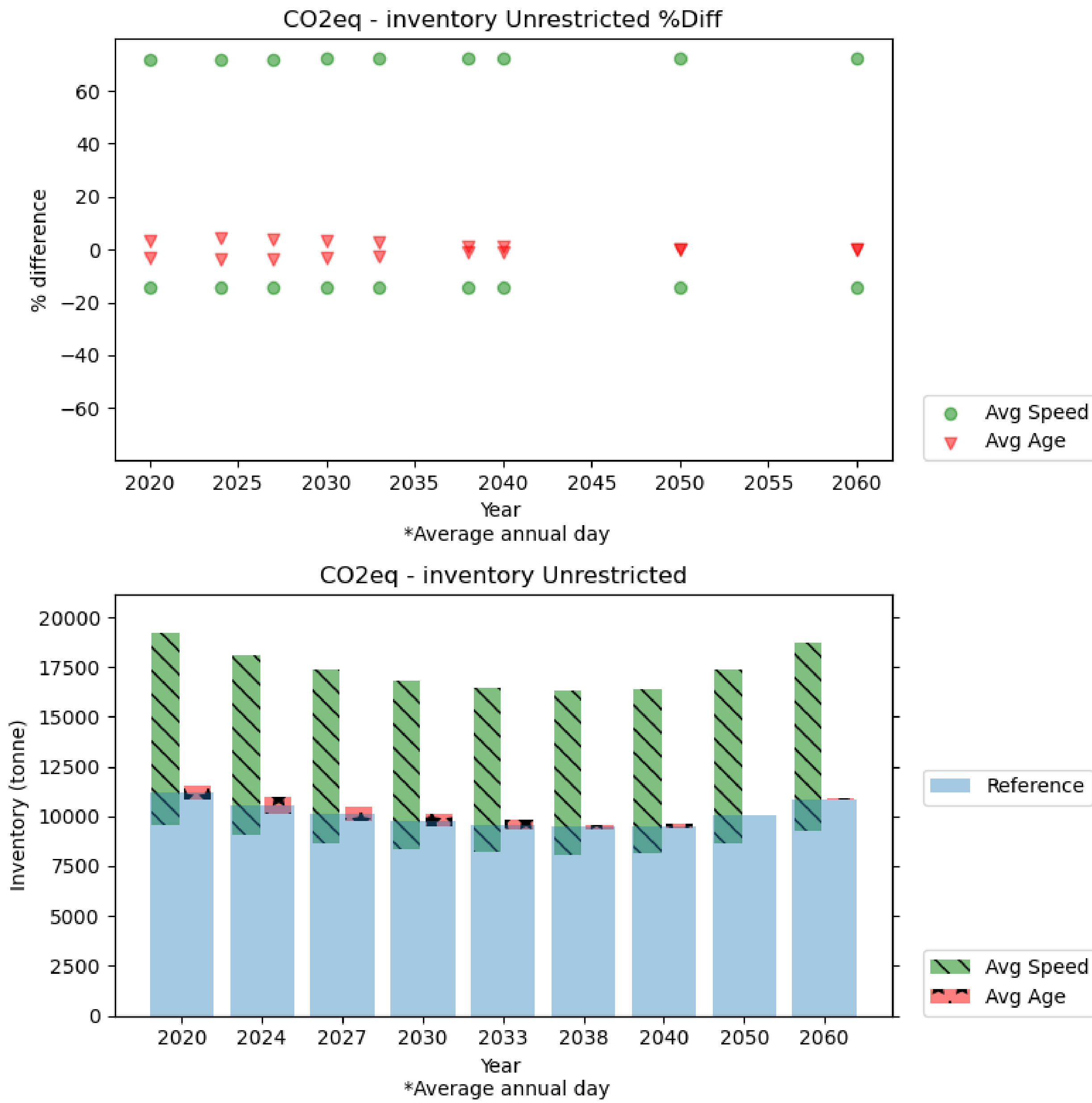


Figure 25. CO_2eq Unrestricted Access Roads Inventory



For the restricted inventory, the average speed scenarios have a range of emissions results that are skewed greater than the reference case and a positive percent difference for $PM_{2.5}$ (Figure 26), NO_x (Figure 27), and CO_2eq (Figure 28). Although $PM_{2.5}$ follows the same trend as the total inventory, the sensitivity to speed is more significant for both the unrestricted and restricted road inventories (e.g., 200% in the out years). As with the unrestricted access inventory, hotelling and ONI scenarios are omitted for the following restricted access inventory figures.

Figure 26. $PM_{2.5}$ Restricted Access Roads Inventory

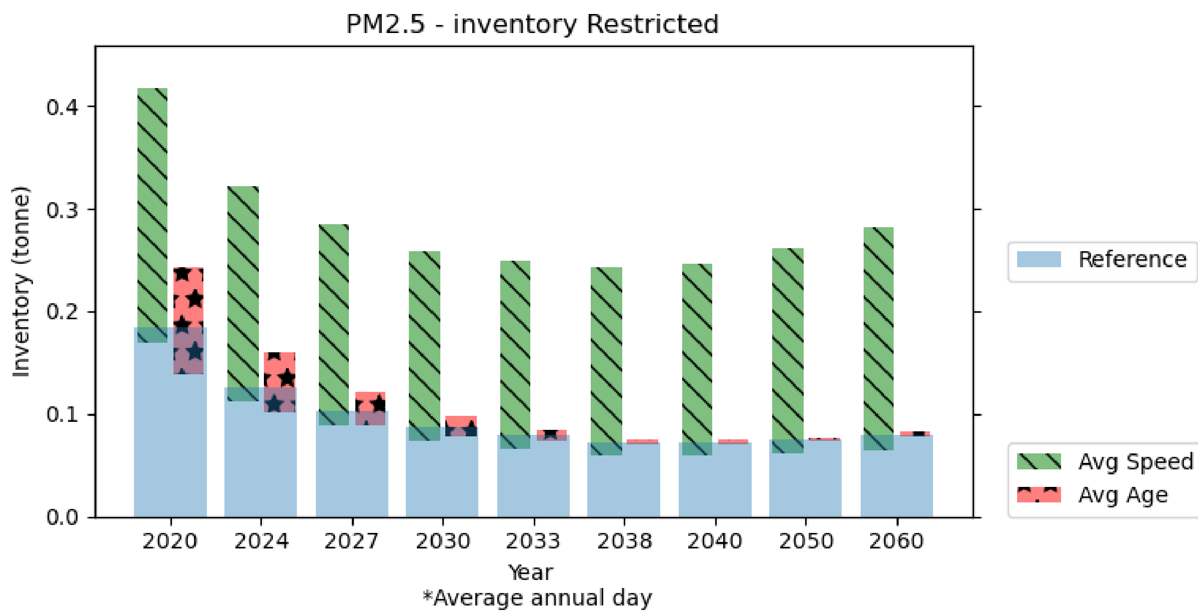
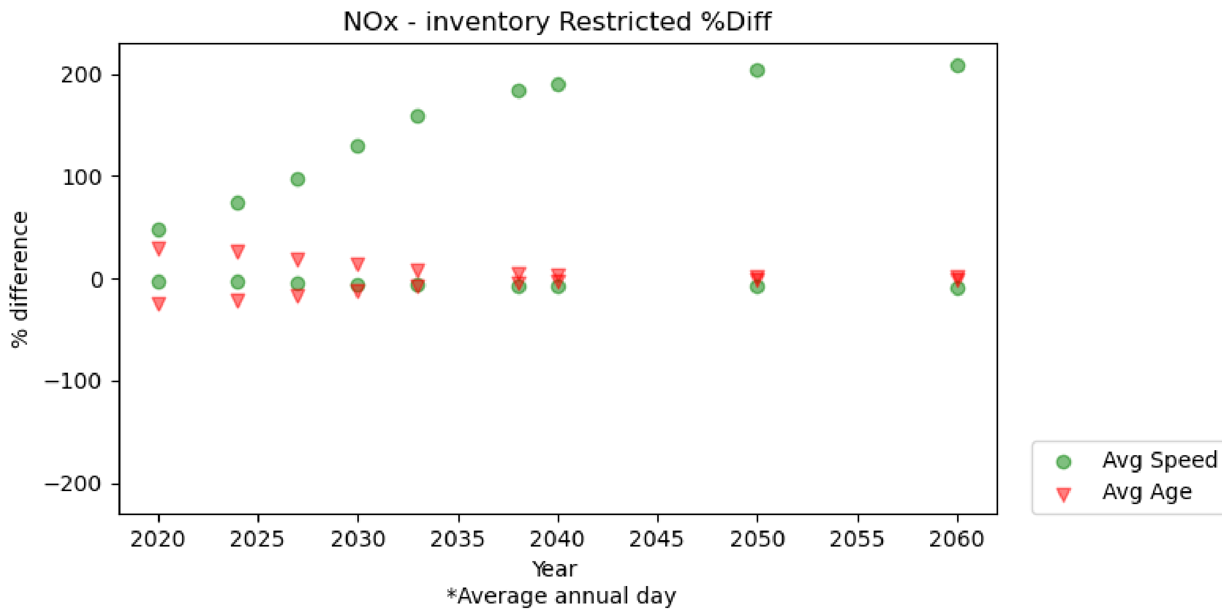


Figure 27. NO_x Restricted Access Roads Inventory



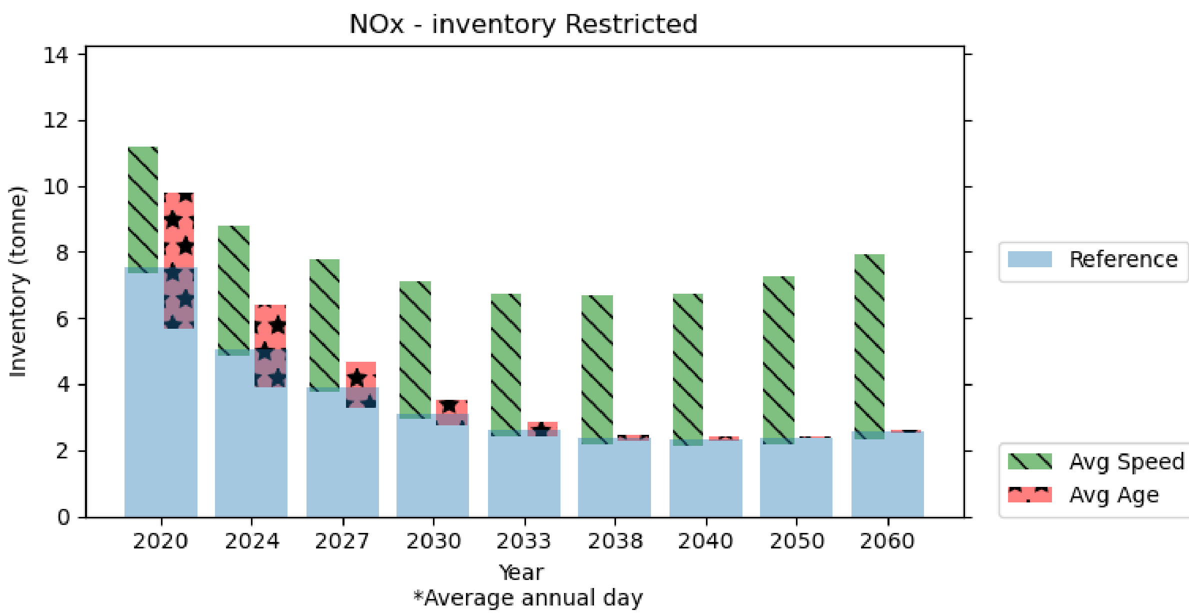
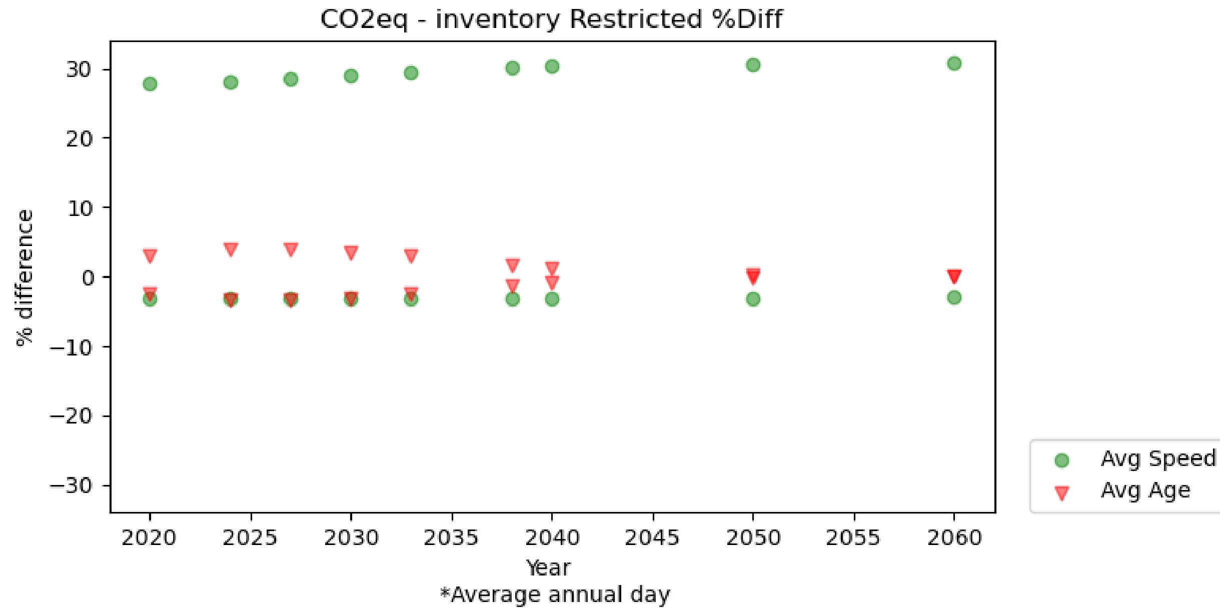
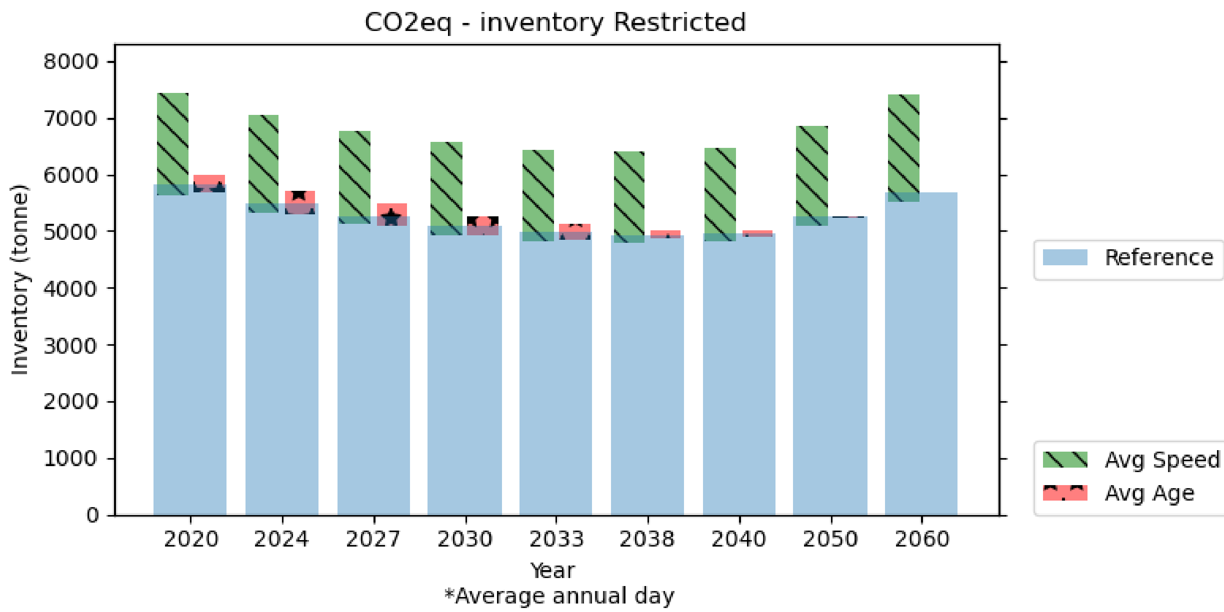


Figure 28. CO_2eq Restricted Access Roads Inventory





Urban and Rural Inventories

The rural inventory includes restricted and unrestricted access rural roads (road types 2 and 3, respectively) aggregated across the county (including all source types and processes). The urban inventory includes restricted and unrestricted access urban roads (road types 4 and 5, respectively) aggregated across the county (including all source types and processes).

When examined specifically on the urban or rural road types, scenarios where average speed distribution inputs were modified show the greatest differences in sensitivity for all pollutants compared to the total inventory results that include all road types. This is most likely due to the fact that the default speed distributions used in the reference case runs are different for urban and rural roads. However, in the scenarios results, speed distributions are the same for all road types. Conversely, in the runs where age distribution inputs were modified, both rural and urban road types show similar results to the cumulative inventory. Since hotelling and ONI scenarios are relevant only for off-network road types, these scenarios are thus omitted from the urban and rural inventory plots. Shown below are the urban (refer to Figure 29 and Figure 30) and rural inventories (refer to Figure 31 and Figure 32) for NO_x and CO_2eq; plots of other pollutants can be found in Appendix E – Complete Inventory Sensitivity Results.

The percent difference between urban emissions inventory for the average speed scenarios resembles that of the total emissions inventory, but the rural emissions inventory has a greater percent difference, and therefore greater sensitivity. The default speed distribution for rural roads (refer to Figure 12 and Appendix B – Scenario Development) generally has free-flow of traffic with little congestion, while many of the average speed scenarios have a range of congestion[16], resulting in an increase in emissions across most of the average speed scenarios.

[16] In other words, they have some significant fractions in the lower speed bins of the average speed distribution table.

Figure 29. NO_x Urban Roads Inventory

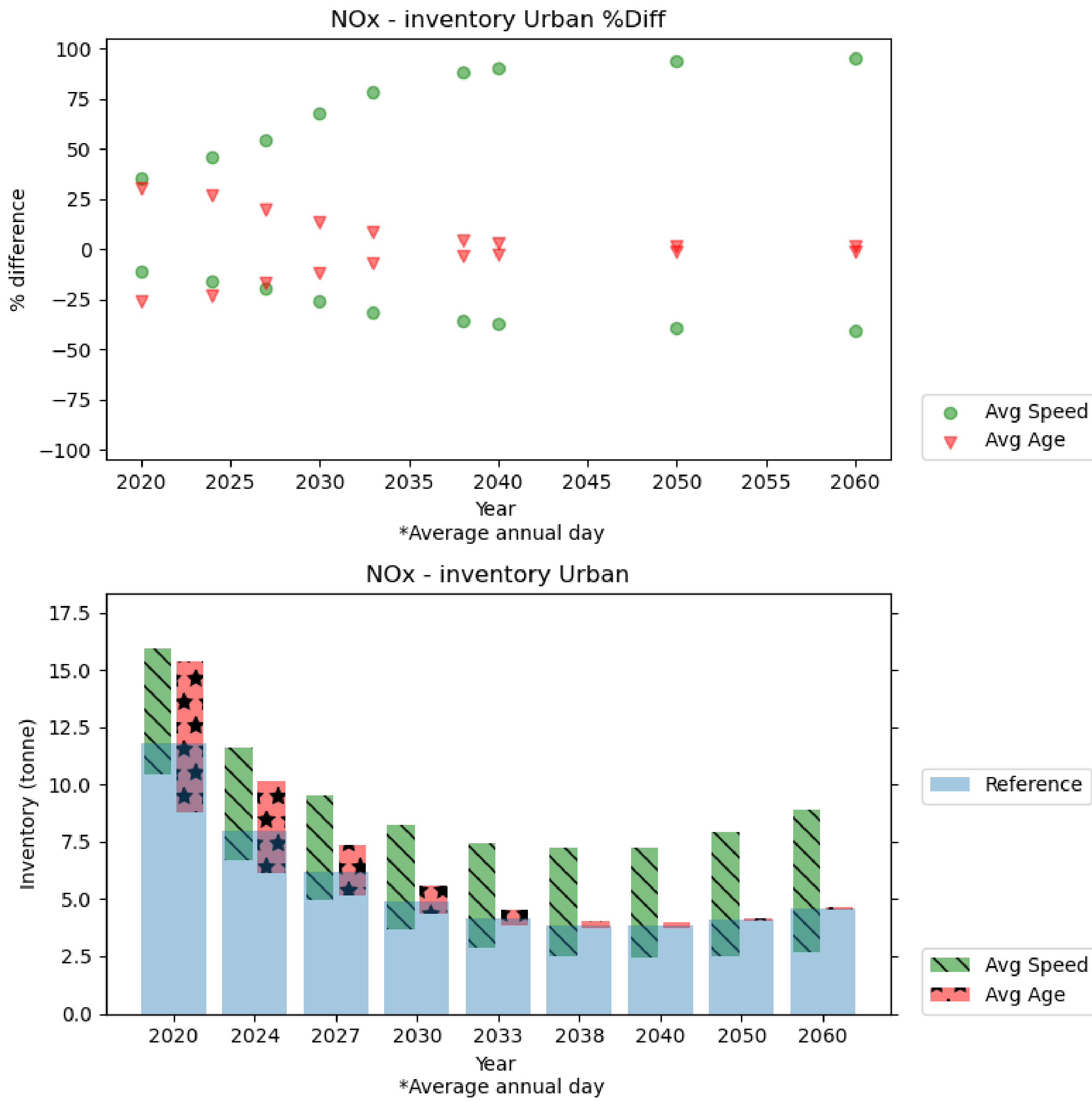


Figure 30. CO_2eq Urban Roads Inventory

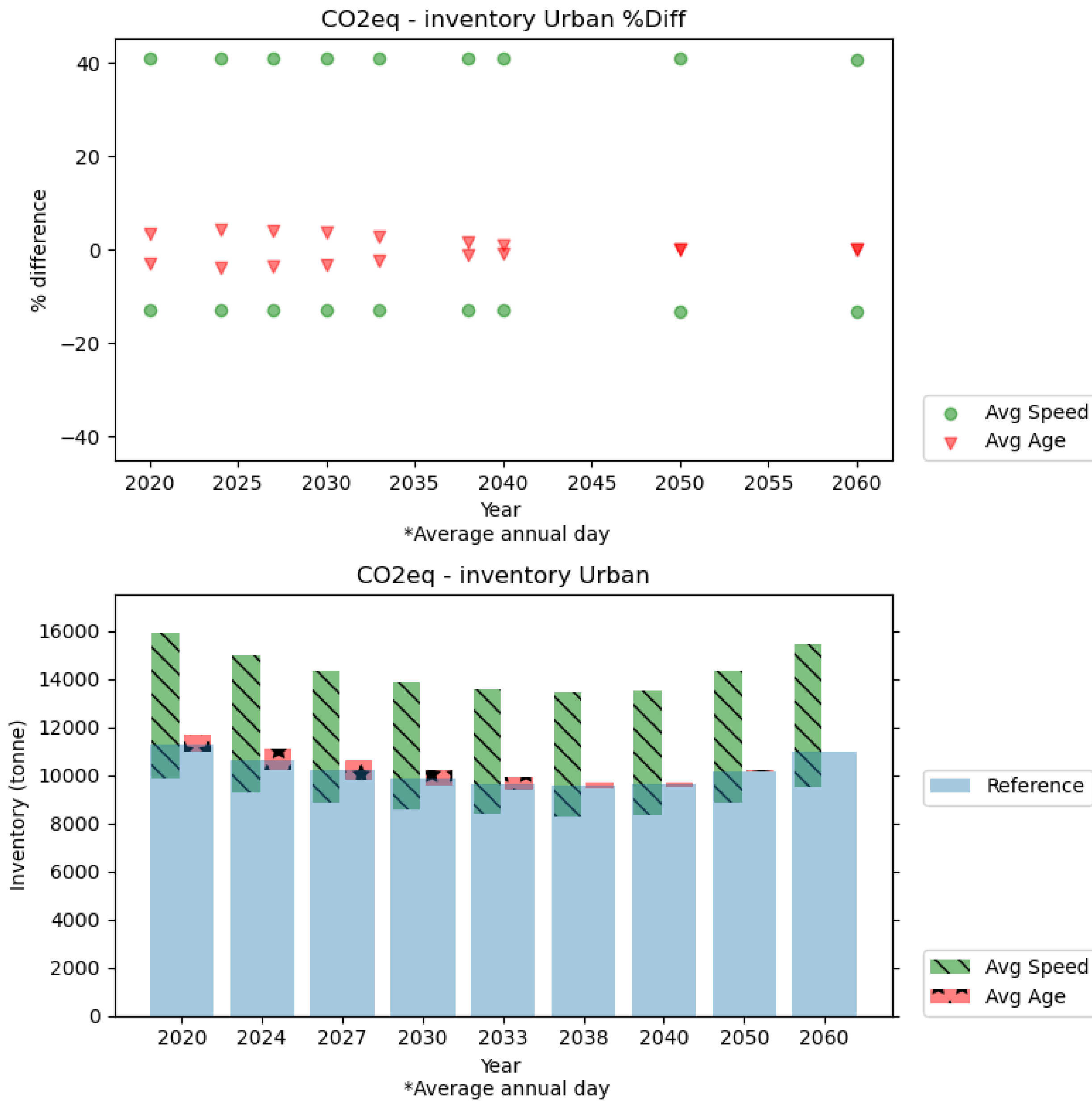


Figure 31. NO_x Rural Roads Inventory

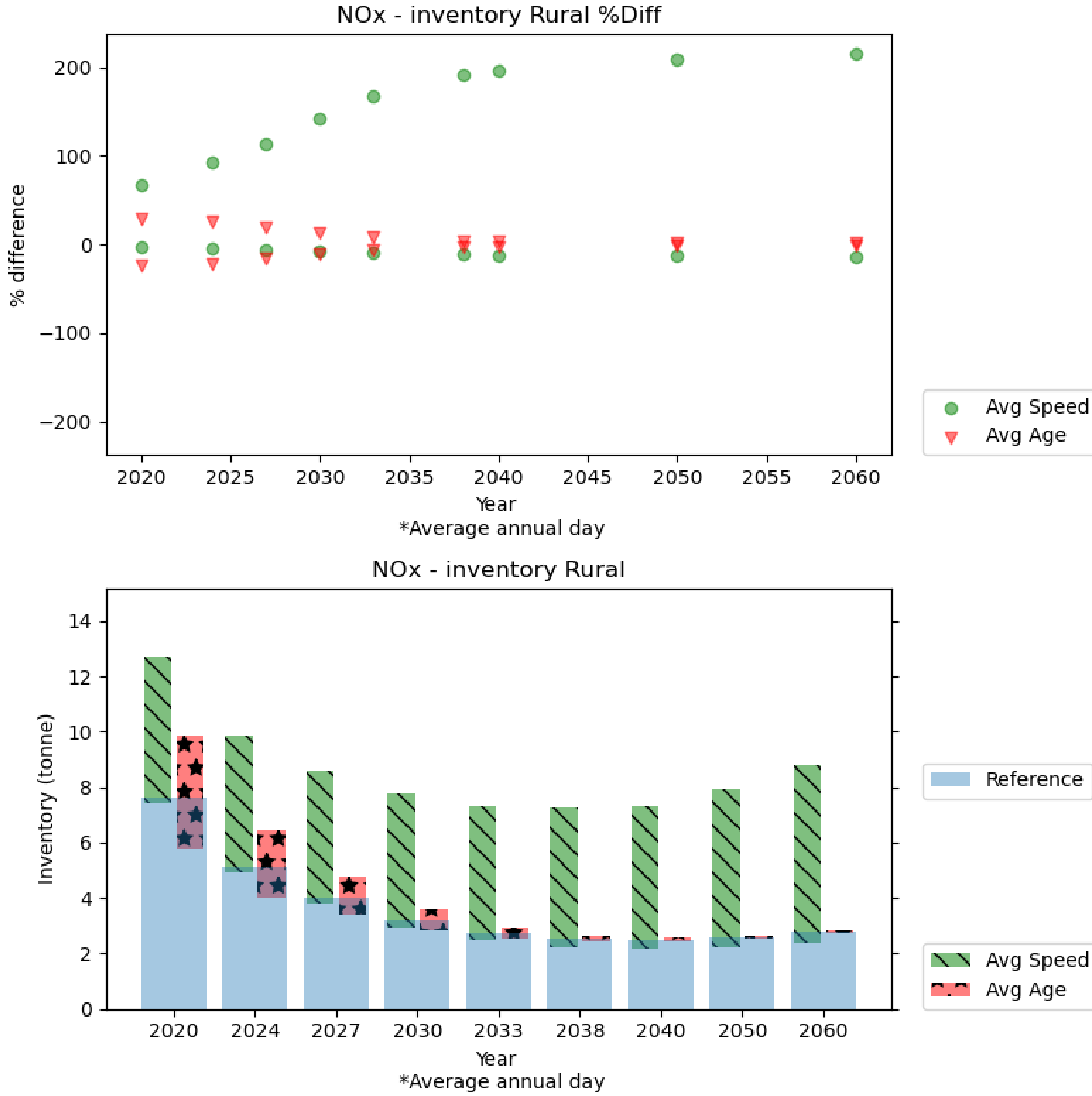
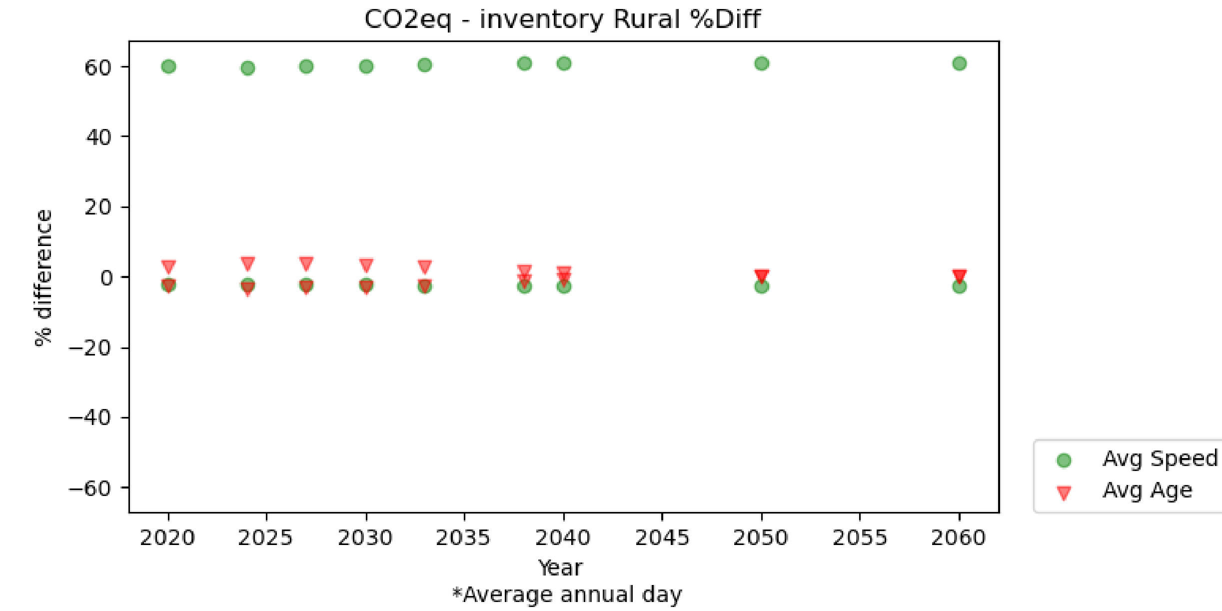
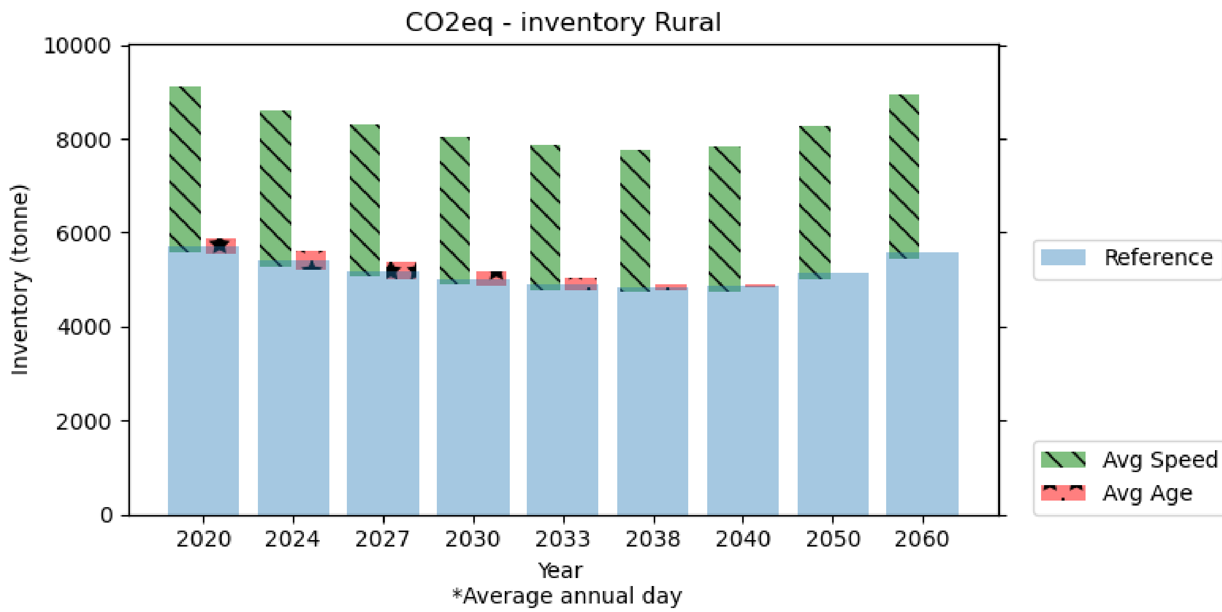


Figure 32. CO_2eq Rural Roads Inventory





Conclusion and Recommendations

The sensitivity analysis described in this report showed that average speed distributions have the greatest overall impact on emissions inventories in MOVES3, with substantial (15 to 50 percent difference from the reference case) to very substantial sensitivity (greater than 50 percent difference) across the various pollutants. Age distribution shows the most variation in sensitivity across the pollutants, from modest (less than 5 percent difference from the reference case) for PM_{10} and CO_2eq to moderate (5 to 15 percent difference from the reference case) for NO_x and $PM_{2.5}$ to substantial for VOC and CO. Hotelling has modest sensitivity for all pollutants while ONI has moderate sensitivity for NO_x and CO_2eq but modest for other pollutants. Thus, the sensitivity of MOVES3 inventories to average speed and age distributions inputs emphasizes the importance of including county-specific age and speed distributions when performing emissions inventory analyses with MOVES3. For more details on the overall impacts, see Table 4.

This study also highlighted interesting interactions between county level database inputs and emissions inventories. For instance, MOVES3 calculates off-network idle hours using a total fraction of source hours operating that is spent idling on and off-network. Changing average speed distributions will also impact off-network idle time when users use the total idle fraction method of idle time inputs in MOVES3. Additionally, age distributions impact the total VMT in different source type categories because MOVES3 takes into account miles driven by different model years when it distributes VMT from HPMS vehicle type to source types.

Sensitivity results of specific inventory focus areas vary from the overall conclusions discussed above in some cases. Cumulative inventories aggregated across all road types, vehicle types, and processes mask changes to the inventories resulting from specific combinations of roads and fleet populations used in project-level MOVES runs or in analyses of subsets of the inventory for policy implications. For example:

- Project year:
    - For total inventory analysis, age distribution shows higher sensitivity in the near-term due to effects of regulatory actions.
- Heavy-duty vehicles
    - Sensitivity to average speed: MOVES3 has updated running rates for heavy-duty diesel vehicles that are meant to represent less effective NO_x controls during idle, low speeds, and low power operations. Under congested traffic conditions, MOVES3 users should expect higher NO_x emissions for these vehicle types compared to conditions with faster speed distributions.
    - Hotelling and source type 62: Hotelling is only applicable to combination long-haul trucks (source type 62), resulting in very small percent differences in the aggregate inventory from the reference case in these scenarios.
- Off-network and average speed:
    - For off-network inventories, ONI has a substantial impact on NO_x and a very substantial impact on CO_2eq.
    - Average speed scenarios show a greater negative percent difference for $PM_{2.5}$, NO_x, and CO_2eq for off-network inventories. These results align with the expectation that the overall average speed distributions will affect the total number of hours idling on and off the roadway network when the lowest speed bin distribution changes. Section 4.12 in EPA's MOVES3 Technical Guidance provides recommendations on using the off-network idling input tables in county level MOVES runs. [1]

The results of this sensitivity testing may be of interest to those using MOVES to model on-road emissions of criteria pollutants, air toxics, and greenhouse gases. Though this sensitivity analysis further emphasizes the importance of using local inputs to generate the most accurate emission inventories, the information provided in this report as well as the post-processed data and databases used in the analyses may help modelers prioritize data collection and assist in interpreting results.

References

[1] U.S. Environmental Protection Agency (EPA), "MOVES3 Technical Guidance: Using MOVES to Prepare Emission Inventories for State Implementation Plans and Transportation Conformity," [Online]. Available: https://www.epa.gov/sites/default/files/2020-11/documents/420b20052.pdf.

[2] U.S. Environmental Protection Agency (EPA), "Overview of EPA's MOtor Vehicle Emission Simulator (MOVES3)," March 2021. [Online]. Available: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1011KV2.pdf.

[3] U.S. Environmental Protection Agency (EPA), "Latest Version of MOtor Vehicle Emission Simulator (MOVES)," 9 December 2022. [Online]. Available: https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves.

[4] U.S. Environmental Protection Agency (EPA), "MOVES3 Update Log," 9 December 2022. [Online]. Available: https://www.epa.gov/moves/moves3-update-log.

[5] U.S. Environmental Protection Agency (EPA), "Population and Activity of Onroad Vehicles in MOVES3," April 2021. [Online]. Available: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1011TF8.pdf.

[6] Federal Highway Administration, "FHWA MOVES3 Sensitivty Analysis Dashboard of Results," 2022. [Online]. Available: https://www.fhwa.dot.gov/environment/air_quality/conformity/methodologies/moves3.cfm.

Appendix A – MOVES Run Specifications

Table 5. MOVES Runspec for Reference Case

Category	Variable	Input
Scale	Model	Onroad
Scale	Domain/Scale	County
Scale	Calculation Type	Inventory
Time Spans	Years	2020, 2030, 2040, 2050, 2060; for conformity: 2024, 2027, 2033, 2038 *(run each year individually)*
Time Spans	Months	January, July
Time Spans	Days	All Selected Weekdays
Time Spans	Hours	All Selected
Geographic Bounds	States	Massachusetts
Geographic Bounds	Counties	Middlesex County (FIPS code 25017)
Geographic Bounds	Selections	Middlesex County, MA (25017)
Onroad Vehicles	Selections	All Fuel/Source Use Type Combinations
Road Type	Road Type	All Available Road Types
Pollutants and Processes	Total Gaseous Hydrocarbons	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust, Evap Permeation, Evap Fuel Vapor Venting, Evap Fuel Leaks, Refueling Displacement Vapor Loss, Refueling Spillage Loss
Pollutants and Processes	Non-Methane Hydrocarbons	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust, Evap Permeation, Evap Fuel Vapor Venting, Evap Fuel Leaks, Refueling Displacement Vapor Loss, Refueling Spillage Loss
Pollutants and Processes	Volatile Organic Compounds	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust, Evap Permeation, Evap Fuel Vapor Venting, Evap Fuel Leaks, Refueling Displacement Vapor Loss, Refueling Spillage Loss
Pollutants and Processes	Methane (CH4)	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Carbon Monoxide (CO)	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Oxides of Nitrogen (NO_x)	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Nitrous Oxide (N2O)	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust

Pollutants and Processes	Primary Exhaust $PM_{2.5}$ – Total	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Primary Exhaust $PM_{2.5}$ – Species	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Primary $PM_{2.5}$ – Brake Wear Particulate	Brake Wear
Pollutants and Processes	Primary $PM_{2.5}$ – Tire Wear Particulate	Tire Wear
Pollutants and Processes	Primary Exhaust PM_{10} – Total	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Primary PM_{10} – Brake Wear Particulate	Brake Wear
Pollutants and Processes	Primary PM_{10} – Tire Wear Particulate	Tire Wear
Pollutants and Processes	Total Energy Consumption (TEC)	Running Exhaust, Start Exhaust, Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Atmospheric CO_2	Running Exhaust, Start Exhaust, Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Carbon Dioxide Equivalent (CO_2e)	Running Exhaust, Start Exhaust, Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Benzene	Running Exhaust, Crankcase Running Exhaust, Start, Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust, Evap Permeation, Evap Fuel Vapor Venting, Evap Fuel Leaks, Refueling Displacement Vapor Loss, Refueling Spillage Loss
Pollutants and Processes	Ethanol	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Evap Permeation, Evap Fuel Vapor Venting, Evap Fuel Leaks, Refueling Displacement Vapor Loss, Refueling Spillage Loss
Pollutants and Processes	1,3-Butadiene	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Formaldehyde	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Acetaldehyde	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Acrolein	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust

Pollutants and Processes	Ethyl Benzene	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Evap Permeation, Evap Fuel Vapor Venting, Evap Fuel Leaks, Refueling Displacement Vapor Loss, Refueling Spillage Loss
Pollutants and Processes	Diesel PM_{10}	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust; Brake Wear; Tire Wear
Pollutants and Processes	Polycyclic Aromatic Hydrocarbons (PAHs) without Naphthalene	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Extended Idle Exhaust, Crankcase Extended Idle Exhaust, Auxiliary Power Exhaust
Pollutants and Processes	Naphthalene gas and particles	Running Exhaust, Crankcase Running Exhaust, Start Exhaust, Crankcase Start Exhaust, Evap Permeation, Evap Fuel Vapor Venting, Evap Fuel Leaks, Refueling Displacement Vapor Loss, Refueling Spillage Loss
General Output	Units	Mass: Grams, Energy: Million BTU, Distance: Miles
General Output	Activity	Distance Traveled, Source Hours, Hotelling Hours, Source Hours Operating, Source Hours Parked, Population, Starts
Output Emissions Detail	Output Aggregation	Time: Day, Geographic: County
Output Emissions Detail	For All Vehicle/Equipment Categories	Model Year, Fuel Type, Emission Process
Output Emissions Detail	Onroad/Nonroad	Onroad: Road Type, Source Use Type, Regulatory Class, Nonroad: <blank>
Advanced Features	Time Aggregation	Hour
Advanced Features	Region Aggregation	County

Table 6. Input Database for Reference Case

Tab	**Data Table**	**Source**
Hotelling	hotellingHoursPerDay, hotellingHourFraction, hotellingAgeFraction, hotellingMonthAdjust, hotellingActivityDistribution	Exported default tables from the County Data Manager and then reimported hotellingActivityDistribution data. All other tables left empty and allowed MOVES to populate defaults at run-time
Idle	totalIdleFraction, idleModelYearGrouping, idleMonthAdjust, idleDayAdjust	Exported default tables from the County Data Manager, and then reimported totalIdleFraction data. All other tables left empty and allowed MOVES to populate defaults at run-time
I/M Programs	IMCoverage	Select ‘no I/M’ coverage checkbox
Retrofit Data	onRoadRetrofit	Preserve prepopulated data for the table in the County Data Manager
Generic	<all tables>	Preserve prepopulated data for all tables in the County Data Manager
Road Type Distribution	roadTypeDistribution	Use roadTypeDistribution table from the national default movesdb20210726 database
Source Type Population	sourceTypeYear	Estimated from a default-scale run for Middlesex County only

Starts	startsPerDayPerVehicle, startsPerDay, startsHourFraction, startsMonthAdjust startsAgeAdjustment, startsOpModeDistribution, starts	Preserve prepopulated data for each table in the County Data Manager
Vehicle Type VMT	HPMSVtypeYear, monthVMTFraction, dayVMTFraction, hourVMTFraction	HPMSVtypeYear data estimated from a default-scale run for Middlesex County only. All other data exported defaults from county data manager and reimported.
Age Distribution	sourceTypeAgeDistribution	Exported defaults and reimported using county data manager.
Average Speed Distribution	avgSpeedDistribution	Exported defaults and reimported using county data manager.
Fuel	FuelSupply	Exported defaults and reimported using county data manager.
Fuel	FuelFormulation	Exported defaults and reimported using county data manager.
Fuel	FuelUsageFraction	Exported defaults and reimported using county data manager.
Fuel	AVFT	Exported defaults and reimported using county data manager.
Meteorology	zoneMonthHour	Exported defaults and reimported using county data manager.

Appendix B – Scenario Development

Hotelling distribution (Scenarios 1-4). Hotelling is defined as any hours that drivers of long-haul combination trucks spend parked during mandated rest times. During hotelling, trucks often idle under load to maintain cabin climate and run accessories.

Hotelling is computed only for diesel long-haul combination trucks and hotelling hours are computed as a fixed ratio to the miles driven on restricted access roads. MOVES3 has three operating modes for hotelling: engine idle (also called extended idle), diesel auxiliary power unit (APU) use, battery or plug-in, and "All Engines and Accessories Off." The allocation of operating modes varies by model year. MOVES3 has updated extended idle rates, reducing the amount of time that trucks are hotelling.

Different types of hotelling have impacts on overall emissions from vehicles. To determine the sensitivity of emission factors to hotelling distribution, MOVES3 runs were conducted on the following scenarios:

1. 100% extended idling
2. 50% extended idling and 50% diesel APU
3. 100% diesel APU
4. 100% truck stop electrification (TSE)

Off-network idling (Scenarios 5-10). Off-network idling (ONI) was added to MOVES3 and is defined as idling activity not associated with drive cycles (beyond idling at traffic signals and in traffic). These ONI activities include idling during pick-up and drop-off of passengers and during deliveries but does not include extended idling. This idling contributes to total emissions but does not take place on the road. Off-network idling emissions rates are the same as other idling rates occurring during drive cycles. These emission rates do not take into account starting, braking, or evaporative emissions. MOVES3 models ONI as running emissions (process ID 1 and 15) on the off-network road type (road type 1) as source hour operating (activity type 4).

MOVES3 includes a new data importer that allows the user to modify the fraction of time vehicles spend idling by source type, monthID, dayID, and model year. The scenarios outlined below for this category were modeled in MOVES by making the appropriate adjustments to the "totalIdleFraction" - accessible through the Off-network idle importer. Default idle assumptions vary by geographic region. However, since this MOVES3 sensitivity analysis uses the default scale and national defaults the national idlefraction was obtained in the reference case movesexecutionDB and subsequently modified for each of the "idleRegionIDs" and "CountytypeIDs" (representing both metropolitan statistical area (MSA) and non-MSA counties).

To determine the potential effect of a range of realistic idle-related policy scenarios, the following variations were modeled (from the reference case) by modifying the appropriate idle fractions:

1. 25% idle decrease for HD vehicle categories 41-62 reflecting a "less effective" local anti-idling ordinance applying to heavy-duty vehicles
2. 75% idle decrease for HD vehicle categories 41-62 reflecting a "more effective" local anti-idling ordinance applying to heavy-duty vehicles

3. 25% idle decrease for all source types reflecting a “less effective” broad local anti-idling ordinance applying to all vehicles[17]
4. 75% idle decrease for all source types reflecting a “more effective” broad local anti-idling ordinance applying to all vehicles
5. 50% idle decrease for transit buses (source type 42) reflecting a “less effective” policy that requires drivers to turn their engine off after five minutes of idle.
6. 90% idle decrease for transit buses (source type 42) reflecting a “more effective” policy that requires drivers to turn their engine off after five minutes of idle.

Figure 33 and Figure 34 illustrate the differences in inputs for total idle fraction for scenario 6 and scenario 10 for some selected examples.

[17] Note, the total idle fraction is zero for motorcycles (11) and motor homes (54) in the MOVES default database, therefore they were not modified in the scenarios.

Figure 33. Reduction in HD total idle fraction for Scenario 6

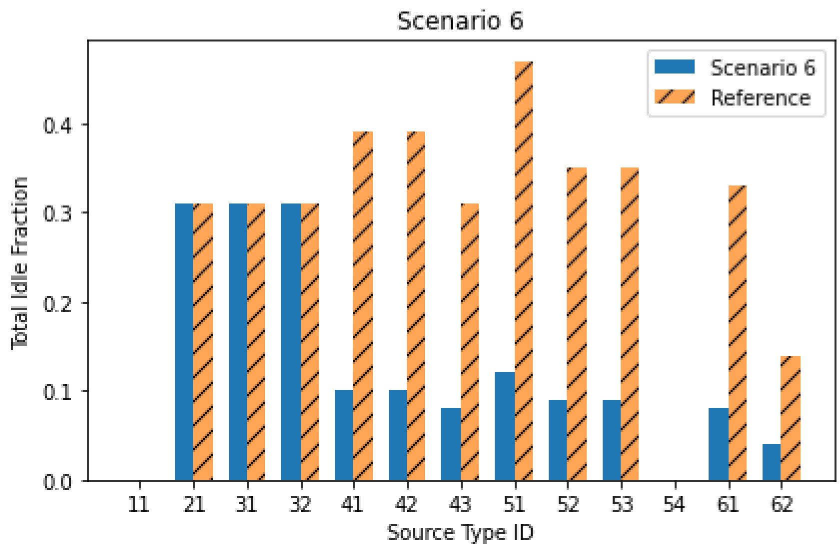
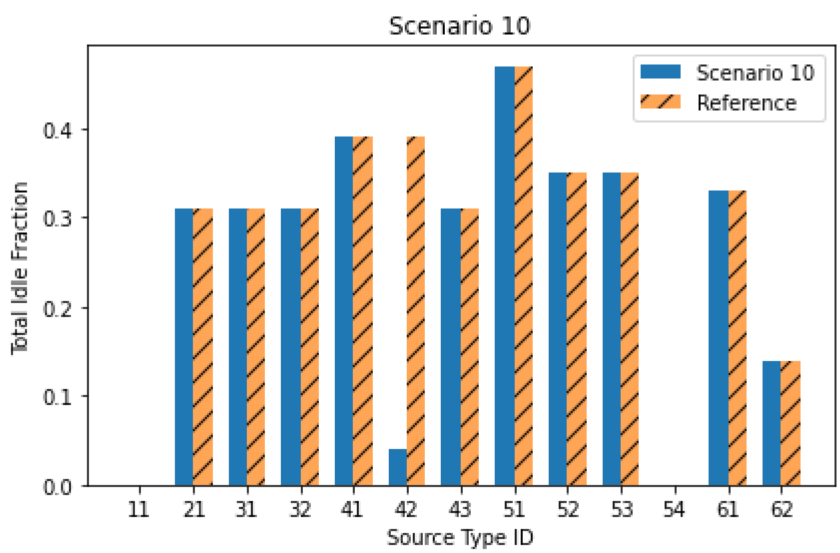


Figure 34. Reduction in transit bus total idle fraction for Scenario 10



Average speed distribution (Scenarios 11-13). The speed distribution is used to determine source hours operating (SHO) units for internal MOVES3 calculations. Speed distribution contributes to operating mode distribution and brake and tire wear. To determine how average speed distributions affect MOVES3 outputs, MOVES3 outputs were compared under different levels of service (LOS) as described in the *Highway Capacity Manual*. Drive schedule data associated with each LOS was taken from the MOVES3 20210209 default database driveschedule and driveschedlesecond tables for three functional classes (FC). The FC and LOS combinations selected represent a range of conditions from free flowing traffic to highly congested traffic depending on the road type. The second-by-second data from the LOS drive schedules was converted to average speed distributions based on the criteria in the avgspeedbin table in the 20210209 default database. Not all LOS data in MOVES is available for each FC which is why the LOS differ for each FC in the following scenarios:

1. Urban and rural restricted access – urban interstate (FC 11): LOS B–F (5 MOVES runs)
2. Urban and rural unrestricted access – urban principal arterial freeway (FC 12): LOS C–E (3 runs)
3. Urban and rural unrestricted access – urban principal arterial other (FC 14): LOS B, C, F (3 runs)

For each scenario, the corresponding drive schedule for each LOS had its own MOVES run, so that MOVES3 outputs could be compared under the different LOS for each FC. Each average speed distribution was mapped to both urban and rural roads for all source types. For example, in scenario 11B, the average speed distribution based on FC11 LOS B replaced the reference average speed distributions on both urban restricted access (road type 2) and rural restricted access (road type 2) for all source types. Figure 35, Figure 36, and Figure 37 illustrate the differences in inputs for speed distribution for scenarios 11, 12, and 13, respectively, for some selected examples. The reference speed distributions are for passenger vehicles (source type 21). Note the reference speed distributions would change for other source types but the scenario speed distributions would be consistent across source types within a specific scenario.

Figure 35. Comparison of Reference speed distribution at 9 am vs Functional Class 11 (Scenario 11)

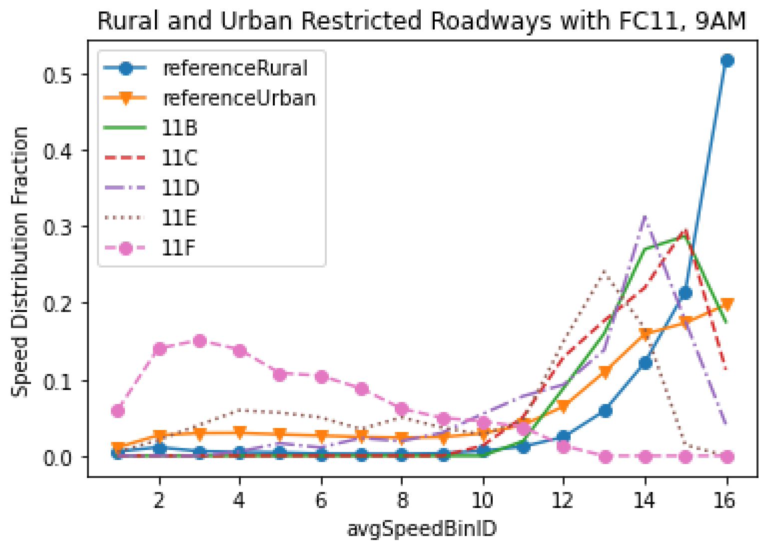


Figure 36. Comparison of Reference speed distribution at 9 am vs Functional Class 12 (Scenario 12)

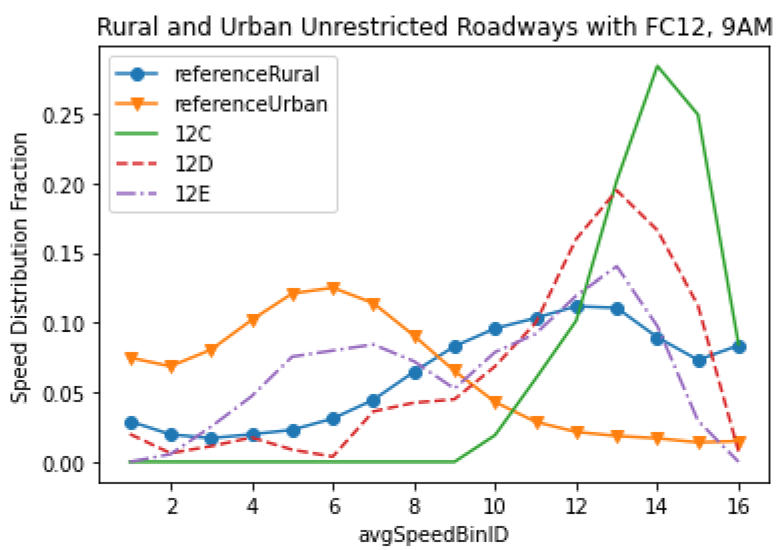
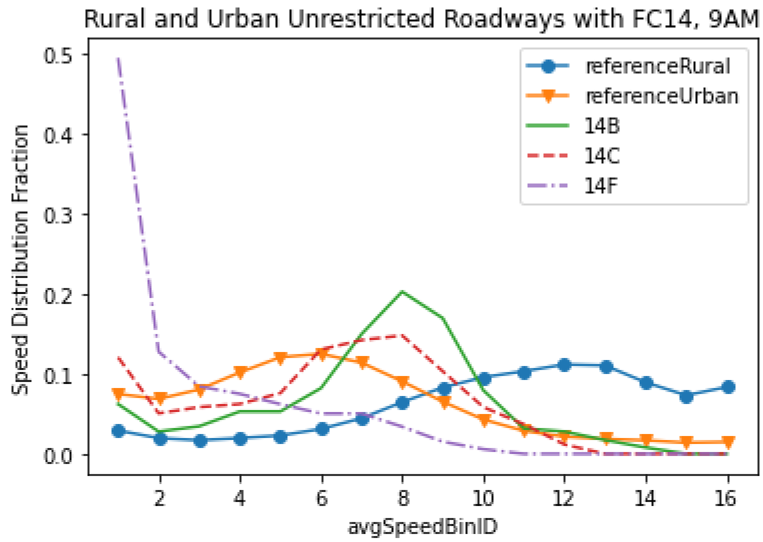


Figure 37. Comparison of Reference speed distribution at 9 am vs Functional Class 14 (Scenario 13)



Age distribution (Scenarios 14-17). Vehicle age is the difference between the model year and the year of analysis and varies every year. MOVES3 updated the age distribution based on newer registration data. It uses registration-based age distributions from years 1990 and 2014. Age distribution for other analysis years are projected forwards or backwards from the 2014 base age distribution.

The baseline case uses the national default average speed distribution for the selected year. Age distributions range from 0 to 30+ years, meaning the age distribution is comprised of 31 fractions. To conduct the sensitivity analysis, the 31 age ranges was divided into three groups. Group 1 consists of vehicles age 0-10, Group 2 is vehicles age 11-20, Group 3 is vehicles age 21-30+. To determine how emission factors change based on the age distribution across all vehicle source types, the following scenarios were run:

4. Increase Group 1 fractions by 10% and decrease Groups 2 and 3 proportionally. This represents a small shift to newer vehicles as compared to the national average.
5. Increase Group 1 fractions by 25% and decrease Groups 2 and 3 proportionally. This represents a larger shift to newer vehicles as compared to the national average.
6. Decrease Group 1 fractions by 10% and increase Groups 2 and 3 proportionally. This represents a small shift to older vehicles as compared to the national average.
7. Decrease Group 1 fractions by 25% and increase Groups 2 and 3 proportionally. This represents a larger shift to older vehicles as compared to the national average.

Figure 38 and Figure 39 illustrate the differences in inputs for age distribution for scenarios 14 through 17 for some selected examples.

Figure 38. Comparison of age distributions of source type 21 for scenarios 14 through 17

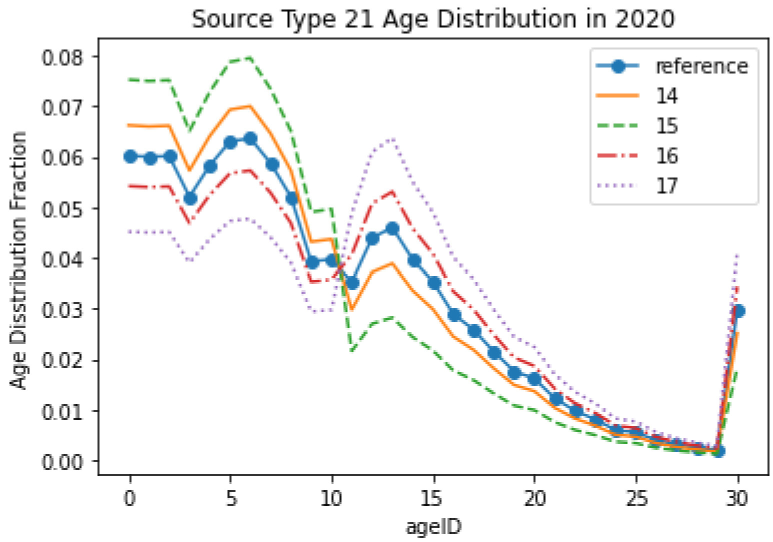
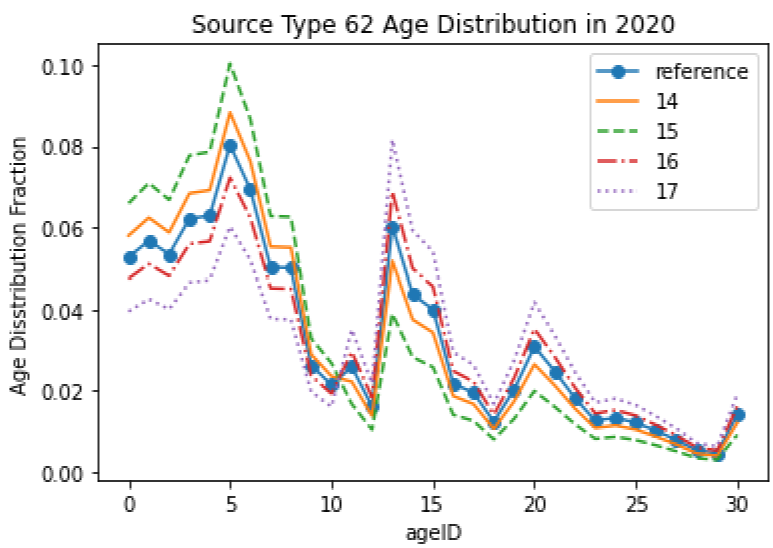


Figure 39. Comparison of age distributions of source type 62 for scenarios 14 through 17



Appendix C – Post-Processing

The following steps describe the overall post-processing:

1. **Quality Control and Error Check**: The first step of post-processing involved checking the expected number of bundles in each output database to ensure the MOVES run completed without error. This check matches the expected bundles with the bundles actually received. If these numbers match, the run can be assumed to have finished without error.
2. **Querying Pollutant Inventories**: The next step queries the moves output inventories for a number of specific pollutants and processes. Running inventories are obtained for running, crankcase running, evaporative, and refueling process types. In addition, brake and tire wear PM emissions are obtained and aggregated into the running emission rates for these on-network processes. Off-network emissions for evaporative and refueling processing are also obtained but processed separately from on-network emissions. Start inventories were aggregated and calculated separately, as well as off- network idle activity. Finally, the various types of hotelling emissions inventories for combination long-haul trucks were aggregated. All of these inventory types were stored in separate variables to allow matching to different activity types depending on the emissions process. For all of these aggregations, inventories were kept disaggregated by year, month, day type, fuel type, source type, road type, and pollutant type.
3. **Querying Activity Quantities**: Next, the relevant activity types for each of the above emissions processes were aggregated and stored in separate variables. This included VMT, population, number of starts, off network idle hours, extended idle hours, diesel APU hours, battery APU hours, and all engines off hotelling hours. For all of these activity value aggregations, activities were kept disaggregated by year, month, day type, fuel type, source type, and road type.
4. **Match Inventories to Activity Quantities**: The next step was to match and join the emissions inventories to the appropriate activity types. Refer to Table 7 for details on the specific process types that were mapped to each activity type. These mapping ensure that there is no "double counting" of emissions inventories in each scenario and year. Inventories in the final dataset can be safely aggregated across different activity types without concern that the same inventories are accounted for multiple times in different process types. After the inventories and activity values were matched, emissions factors were calculated for each row in the resulting table by dividing the inventory by the activity value. The resulting units for each emission factors are also shown in Table 7.
5. **Concatenate All Runs**: The final step concatenates all of the inventory, activity, and emission factor data into one overall dataset for that year in that scenario and saved this as a CSV file. These aggregations and calculations are performed for every scenario and year combination. A secondary post-processing step reads all of the resulting CSV files for all scenarios and years and concatenates these together into an overall dataset for the entire sensitivity analysis. This overall dataset contains the columns shown in Table 8.
6. **Create Overall Results File**: The overall results file contains inventories for two weekdays throughout the year: one in January to represent a winter weekday, and one in July to represent a summer weekday. The results discussed in this report use an average of these two days in order to represent an annual average weekday inventory in the Middlesex, MA county region.

Table 7. Post-processing Mapping of Emission Processes and Road Type to Activity Type

Activity Type ID	Activity	Associated Process IDs	RoadTypeIDs Included	Emission Rate Units	Notes
1	Vehicle Miles Traveled (1)	Running Tailpipe (1), Brake Wear (9), Tire Wear (10), Evap Permeation (11), Evap Fuel Vapor Venting (12), Evap Fuel Leaks (13), Crankcase Running Exhaust (15), Refueling Displacement Vapor Loss (18), Refueling Spillage Loss (19)	Rural Restricted Access (2), Rural Unrestricted Access (3), Urban Restricted Access (4), Urban Unrestricted Access (5)	g/mile	Refueling spillage and vapor loss emissions are calculated from VMT for on-network roadways, so this also accounts for emissions from those processes for VMT on roadway types 2-5.
7	Starts (7)	Start Exhaust (2), Crankcase Start Exhaust (16)	Off-Network (1)	g/start	
6	Population (6)	Evap Permeation (11), Evap Fuel Vapor Venting (12), Evap Fuel Leaks (13), Refueling Spillage Loss (18), Refueling Spillage Loss (19)	Off Network (1)	g/vehicle	Accounts for all evaporative emissions and refueling vapor and spillage loss emissions as calculated by MOVES from source operating hours not on the roadway network and starts
4	Off-Network Idle Hours (4)	Running Tailpipe (1), Crankcase Running Exhaust (15)	Off Network (1)	g/hour	
3	Extended Idle Hours Hotelling (3)	Extended Idle Exhaust (90), Crankcase Extended Idle Exhaust (17)	Off Network (1)	g/hour	Emissions inventories exist only for combination long-haul trucks (sourceTypeID 62) in this category

13	Diesel Auxiliary Power Unit Hotelling (13)	Auxiliary Power Exhaust (91)	Off Network (1)	g/hour	Emissions inventories exist only for combination long-haul trucks (sourceTypeID 62) in this category
14	Battery Auxiliary Power Unit Hotelling (14)	None	Off Network (1)	g/hour	Emissions from this mode of hotelling are 0, and thus emissions rates for these entries will be 0 kg/hour, and inventories will be zero as well
15	All Off Hours Hotelling (15)	None	Off Network (1)	g/hour	Emissions from this mode of hotelling are 0, and thus emissions rates for these entries will be 0 kg/hour, and inventories will be zero as well

Table 8. Column Definition in Final Dataset

Column Name	Definition
scenarioID	ID for the specific scenario
movesRunID	1 for all rows
yearID	The year of the moves run
monthID	The month ID of the data as assigned by MOVES
dayID	The day type ID as assigned by MOVES; 5, or weekday, for all rows
countyID	The county ID as assigned by MOVES; 25017, or Middlesex, MA for all rows
fuelTypeID	The fuel type ID as assigned by MOVES
sourceTypeID	The source type ID as assigned by MOVES
roadTypeID	The road type ID as assigned by MOVES
activitytypeid	The type of activity as assigned by MOVES and matched to the process inventories accounted for in a particular row
activity	The amount of activity of the type indicated in activitytypeID column
pollutantID	The pollutant ID relevant to the inventory recorded in this row *Pollutant ID 100($PM_{2.5}$) and 110(PM_{10}) are mapped to contain exhaust, tire wear and brake wear.
inventory	The amount of pollutant of the type indicated in pollutantID column, produced by the amount of activity indicated in activity column
emissionRate	The rate of emissions per activity
invUnits	Units for inventory column
actUnits	Units for activity column
rateUnits	Units for emissionRate column
regClassID	Regulatory Class ID

Appendix D – MOVES Definitions

Table 9. MOVES Source Types

ID	HPMS Type	Source Type
11	10	Motorcycle
21	25	Passenger Car
31	25	Passenger Truck
32	25	Light Commercial Truck
41	40	Other Buses
42	40	Transit Bus
43	40	School Bus
51	50	Refuse Truck
52	50	Single Unit Short-haul Truck
53	50	Single Unit Long-haul Truck
54	50	Motor Home
61	60	Combination Short-haul Truck
62	60	Combination Long-haul Truck

Table 10. MOVES Road Types

ID	Road Type
1	Off-Network
2	Rural Restricted Access
3	Rural Unrestricted Access
4	Urban Restricted Access
5	Urban Unrestricted Access

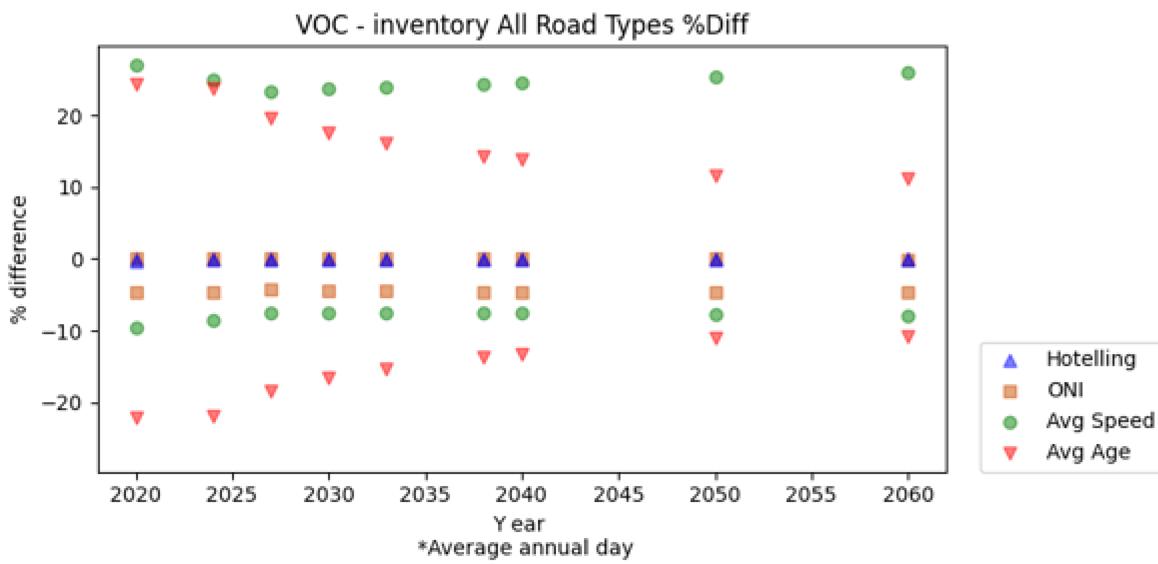
Table 11. MOVES Emission Processes

ID	Process Name
1	Running Exhaust
2	Start Exhaust
9	Brake Wear
10	Tire Wear
11	Evaporative Permeation
12	Evaporative Fuel Vapor Venting
13	Evaporative Fuel Leaks
15	Crankcase Running Exhaust
16	Crankcase Start Exhaust
17	Crankcase Extended Idle Exhaust
18	Refueling Displacement Vapor Loss
19	Refueling Spillage Loss
20	Extended Idle Exhaust
21	Auxiliary Power Exhaust

Appendix E – Complete Inventory Sensitivity Results

Total Inventory

Figure 40. VOC Inventory Total



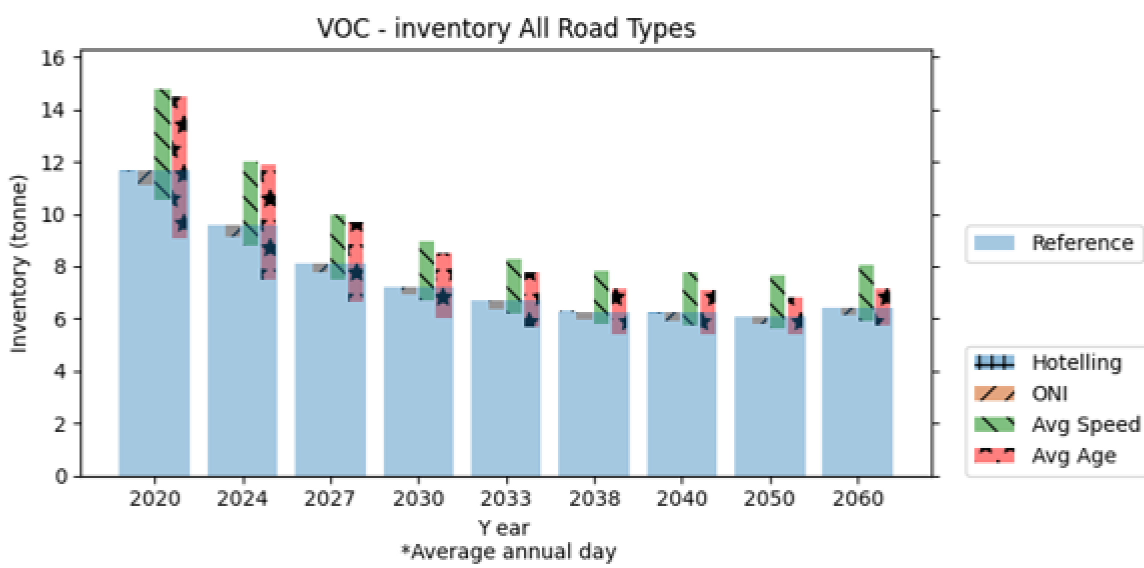
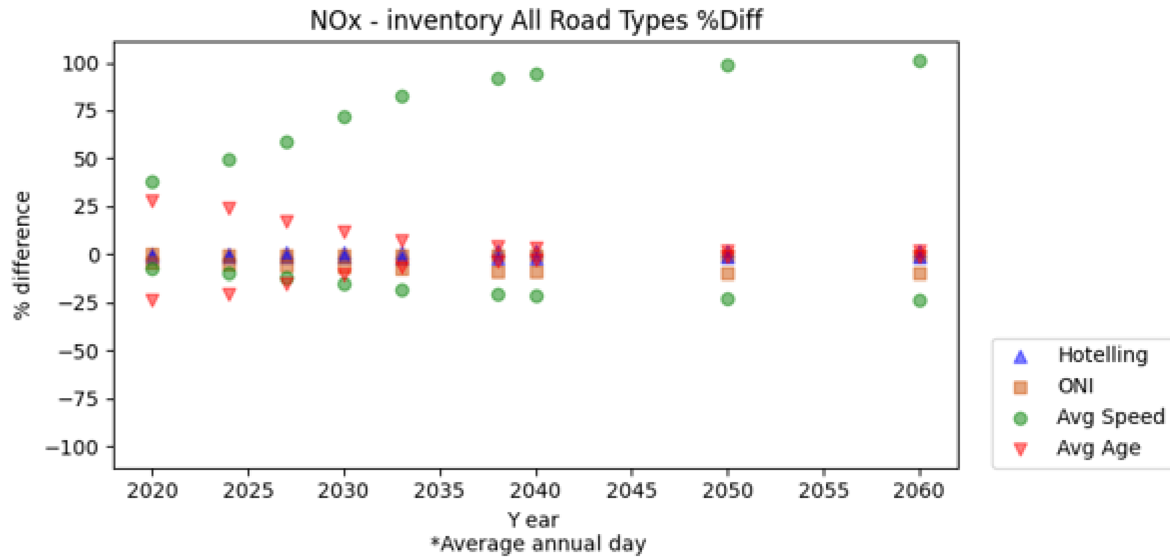


Figure 41. NO_x Inventory Total



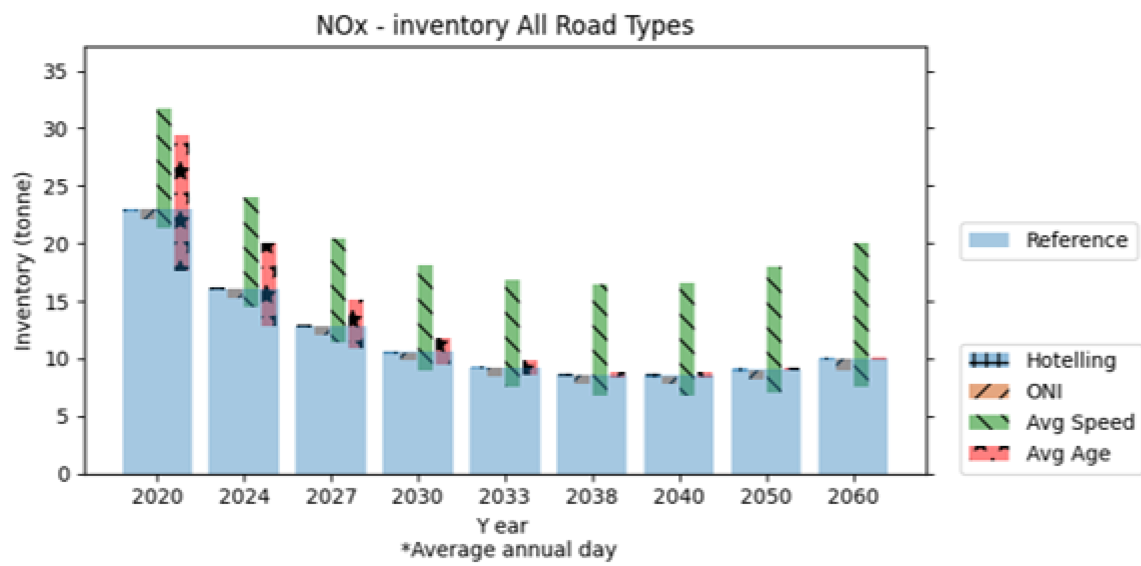


Figure 42. $PM_{2.5}$ Inventory Total

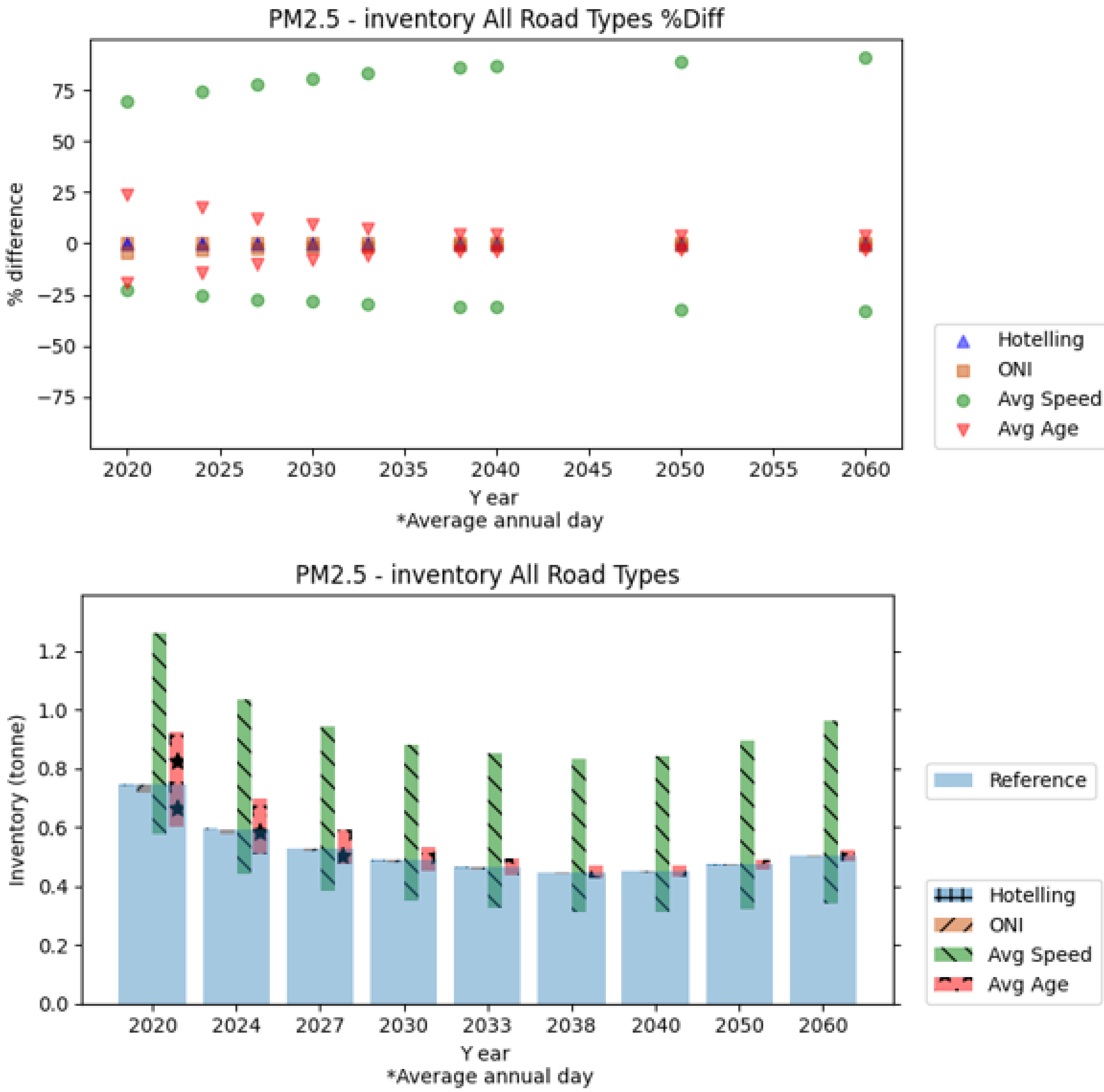
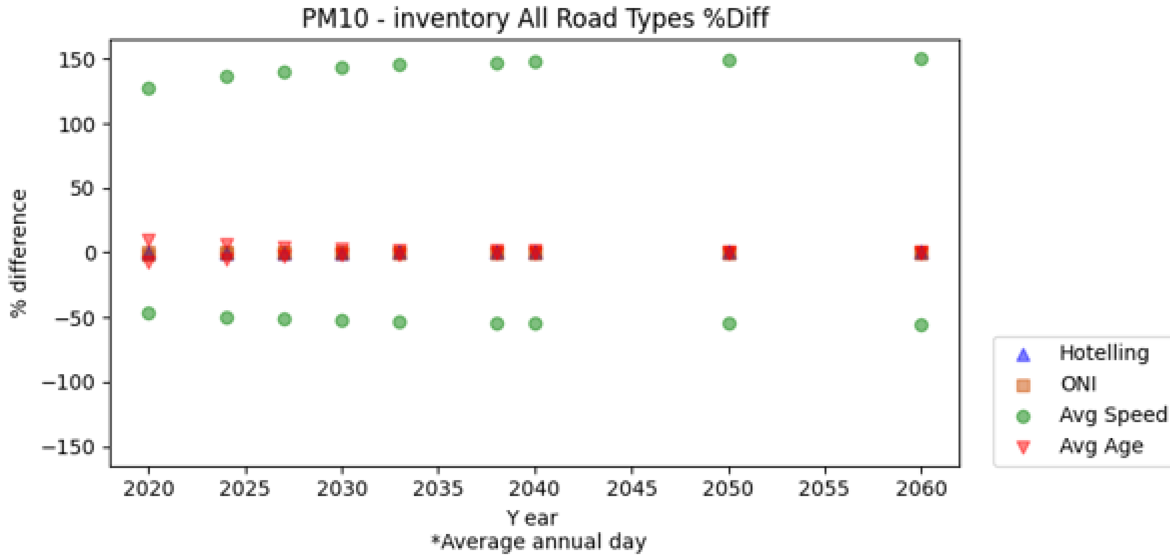


Figure 43. PM_{10} Inventory Total



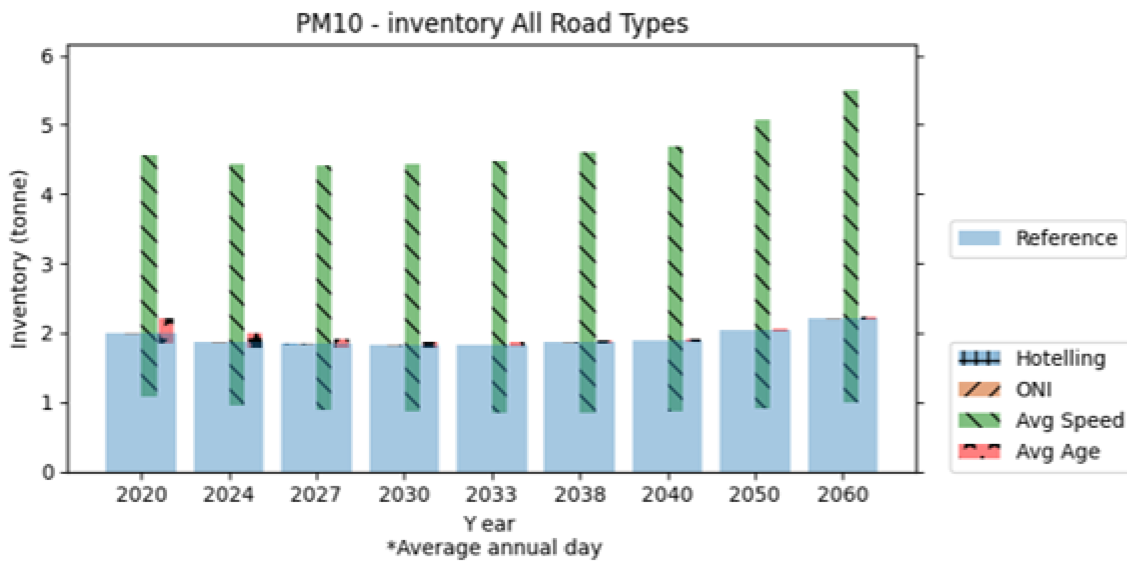
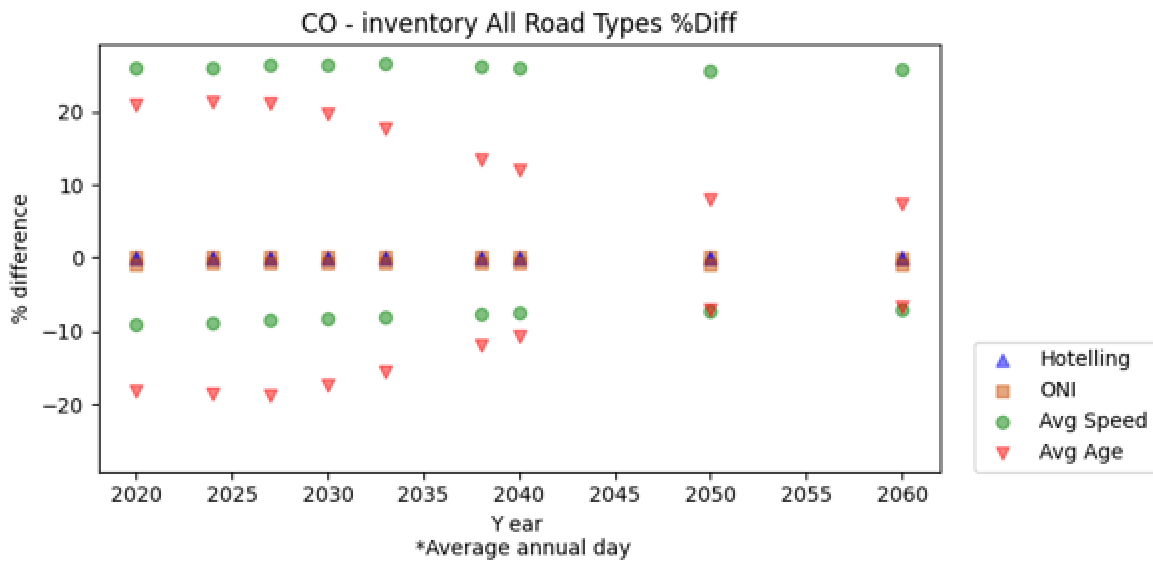


Figure 44. CO Inventory Total



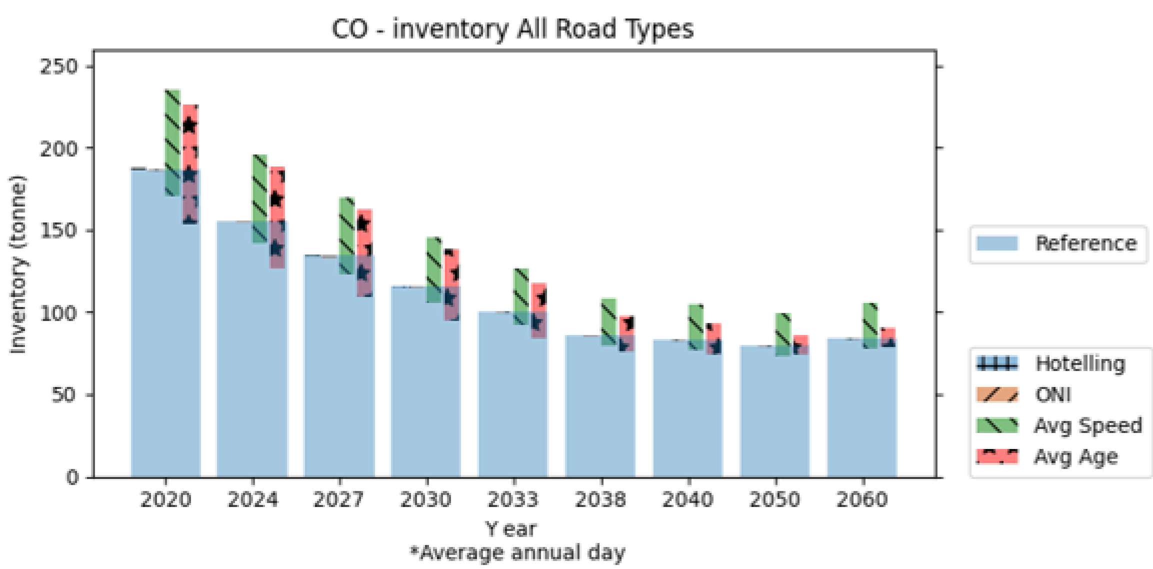
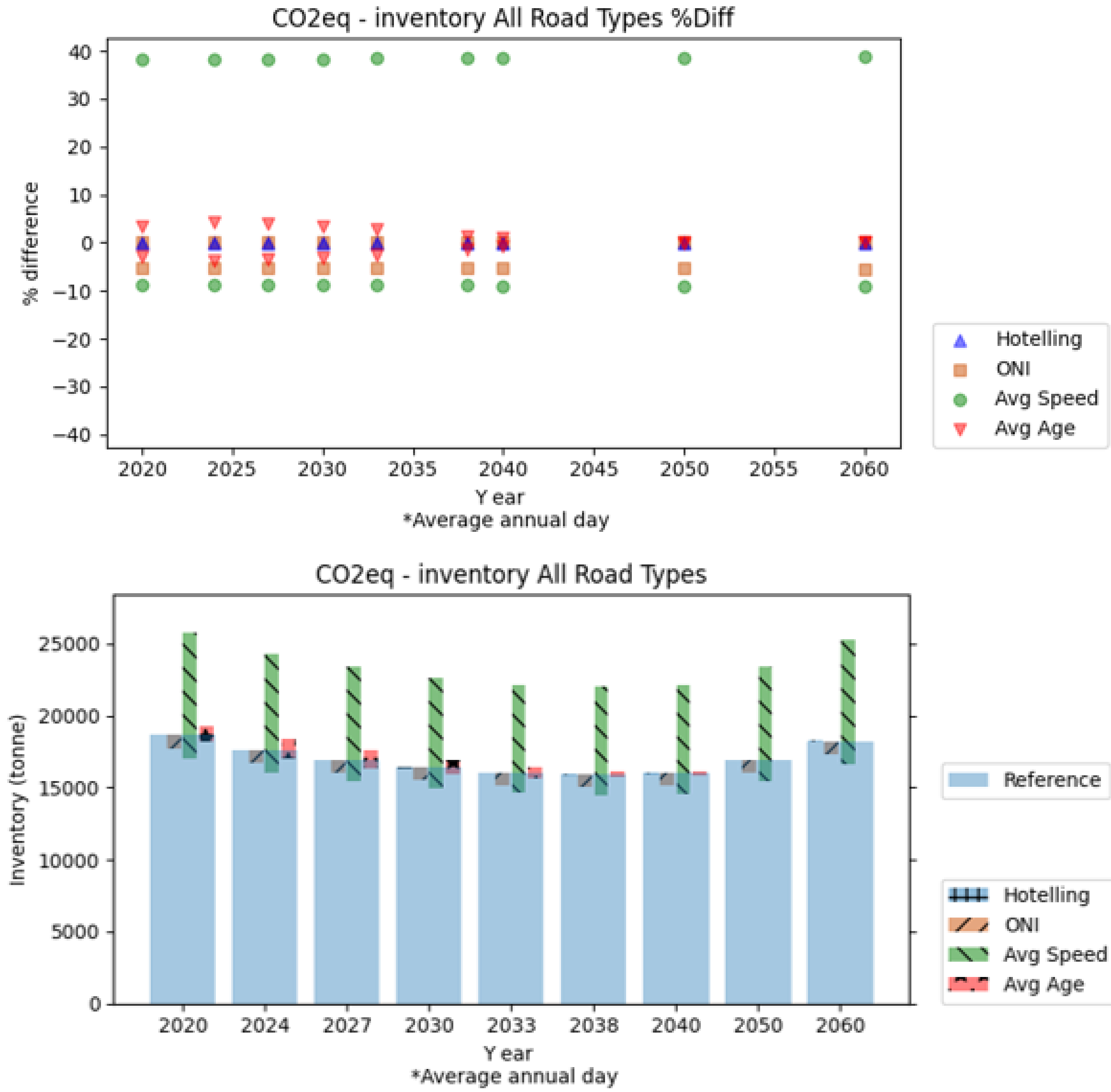


Figure 45. CO_2eq Inventory Total



Light-Duty & Heavy-Duty

Figure 46. VOC Light-Duty Vehicles Inventory

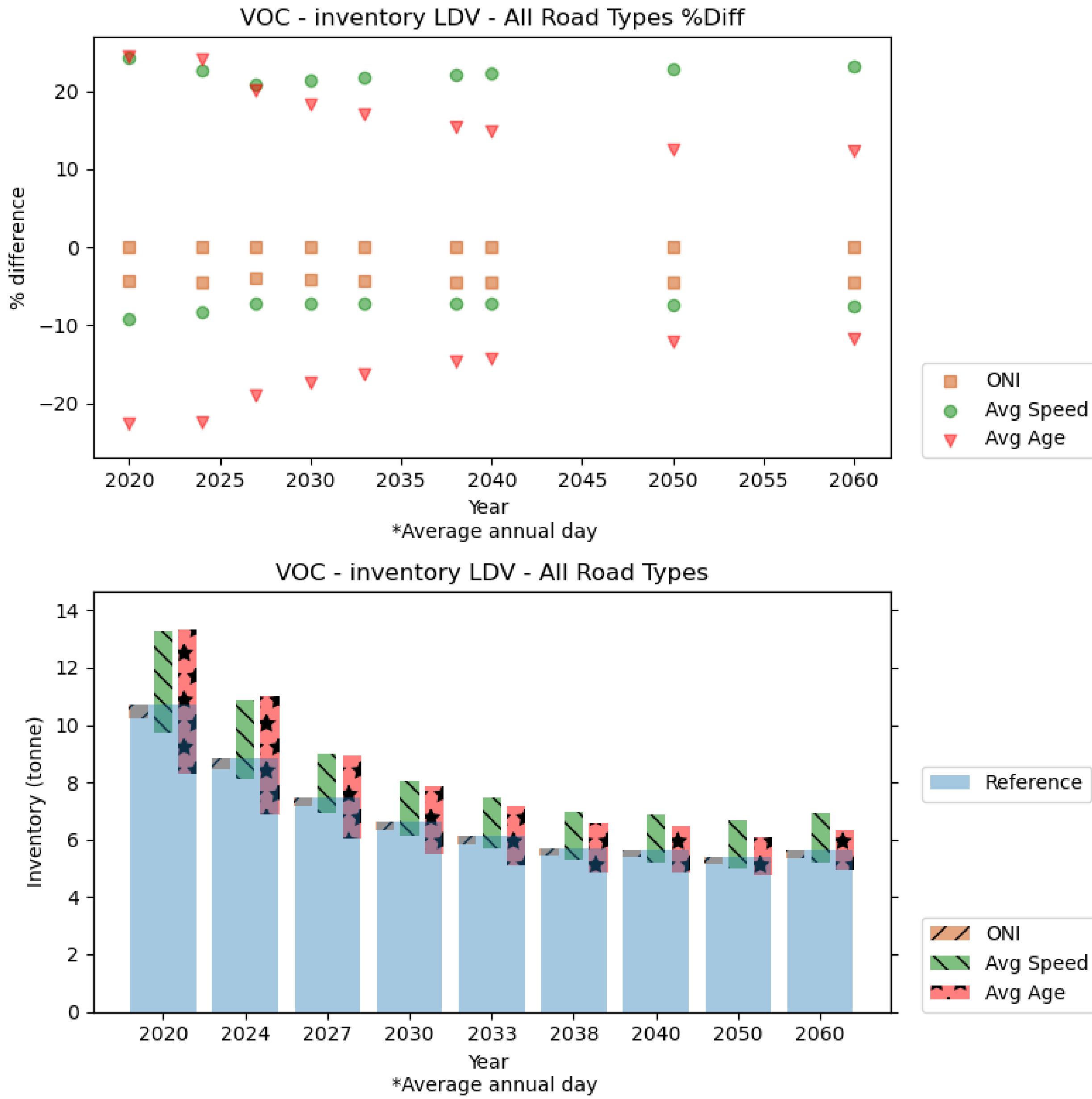
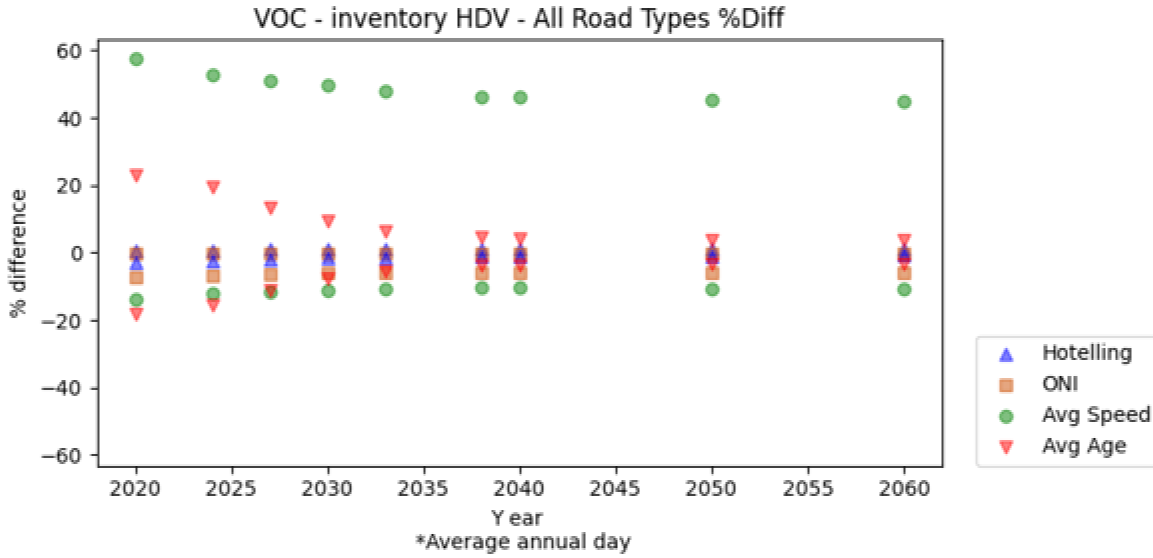


Figure 47. VOC Heavy-Duty Vehicles Inventory



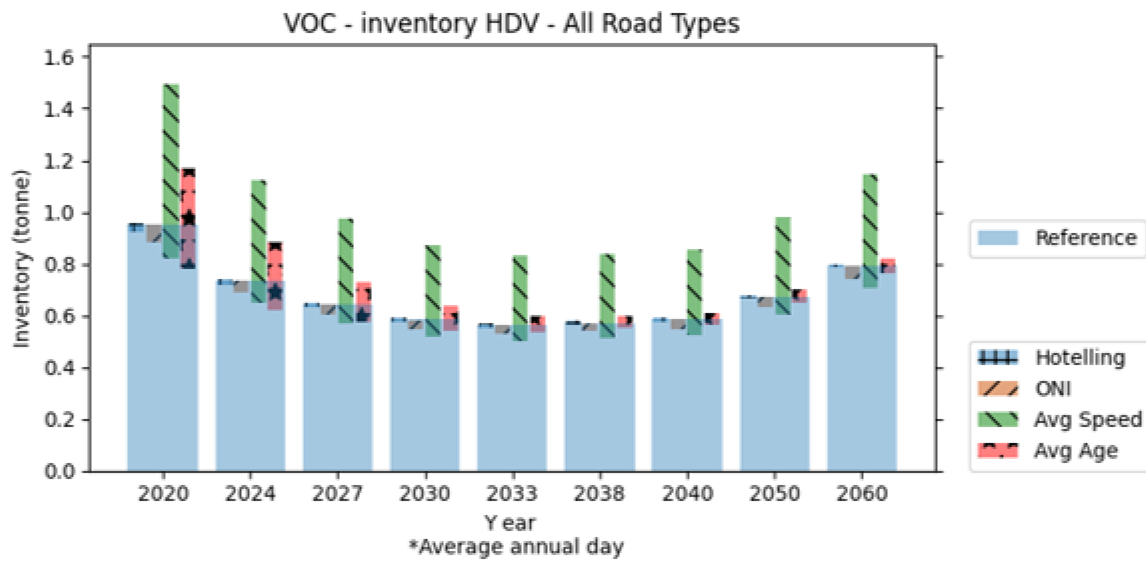


Figure 48. NO_x Light-Duty Vehicles Inventory

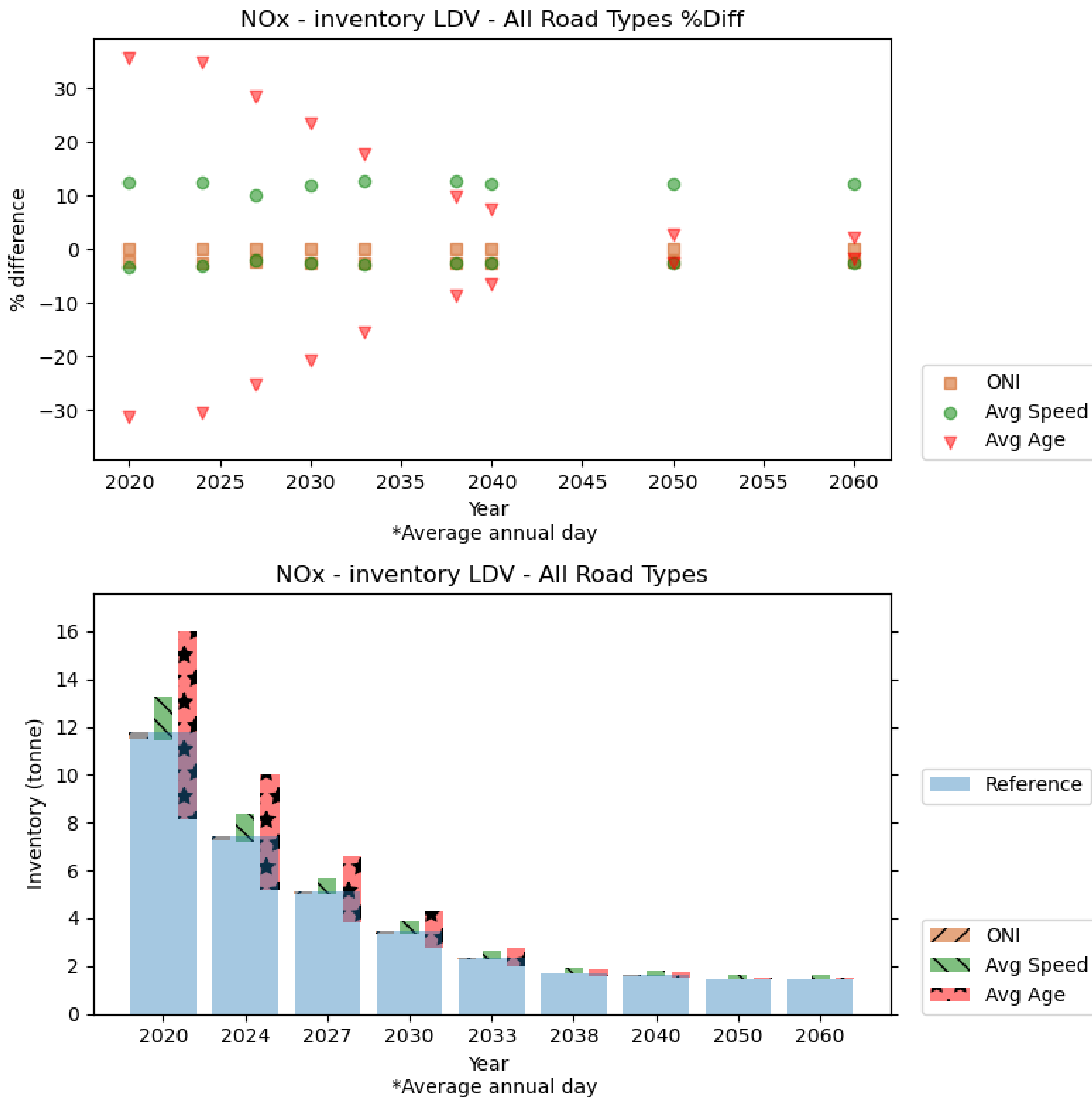
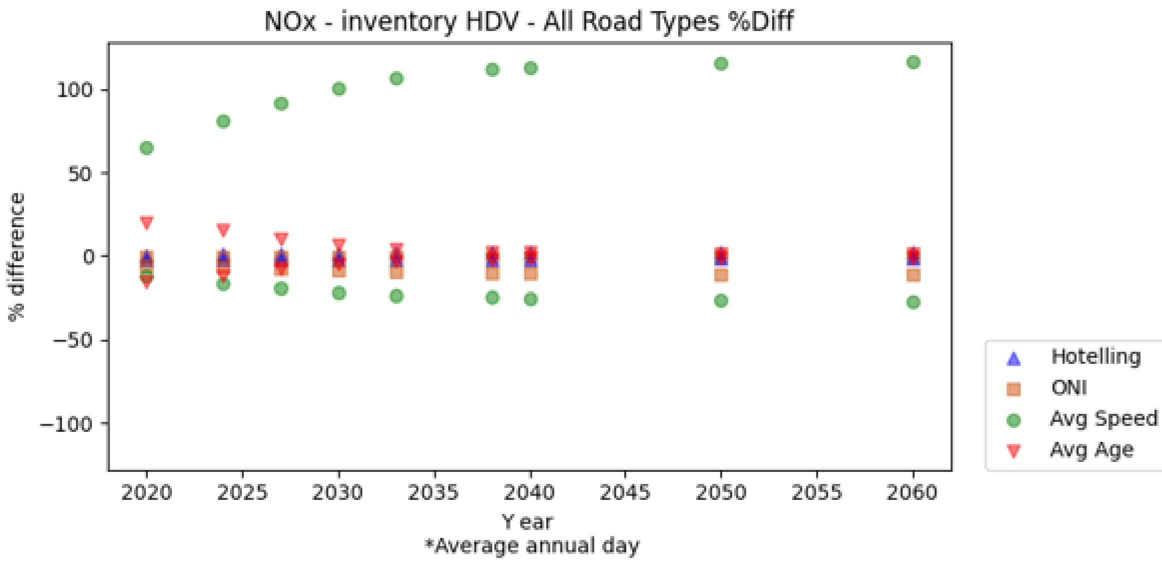


Figure 49. NO_x Heavy-Duty Vehicles Inventory



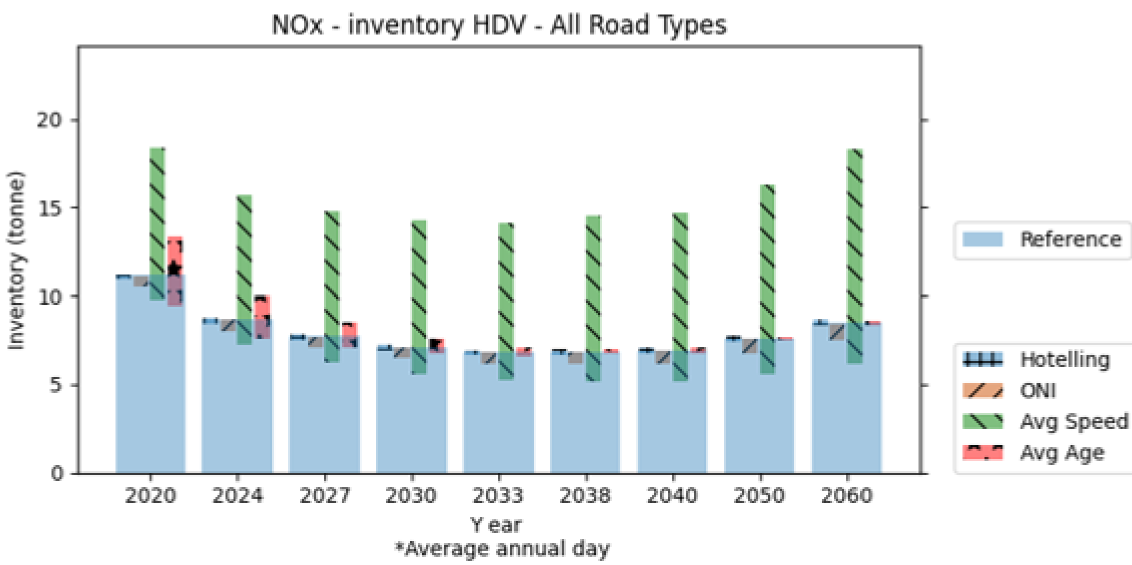


Figure 50. $PM_{2.5}$ Light-Duty Vehicles Inventory

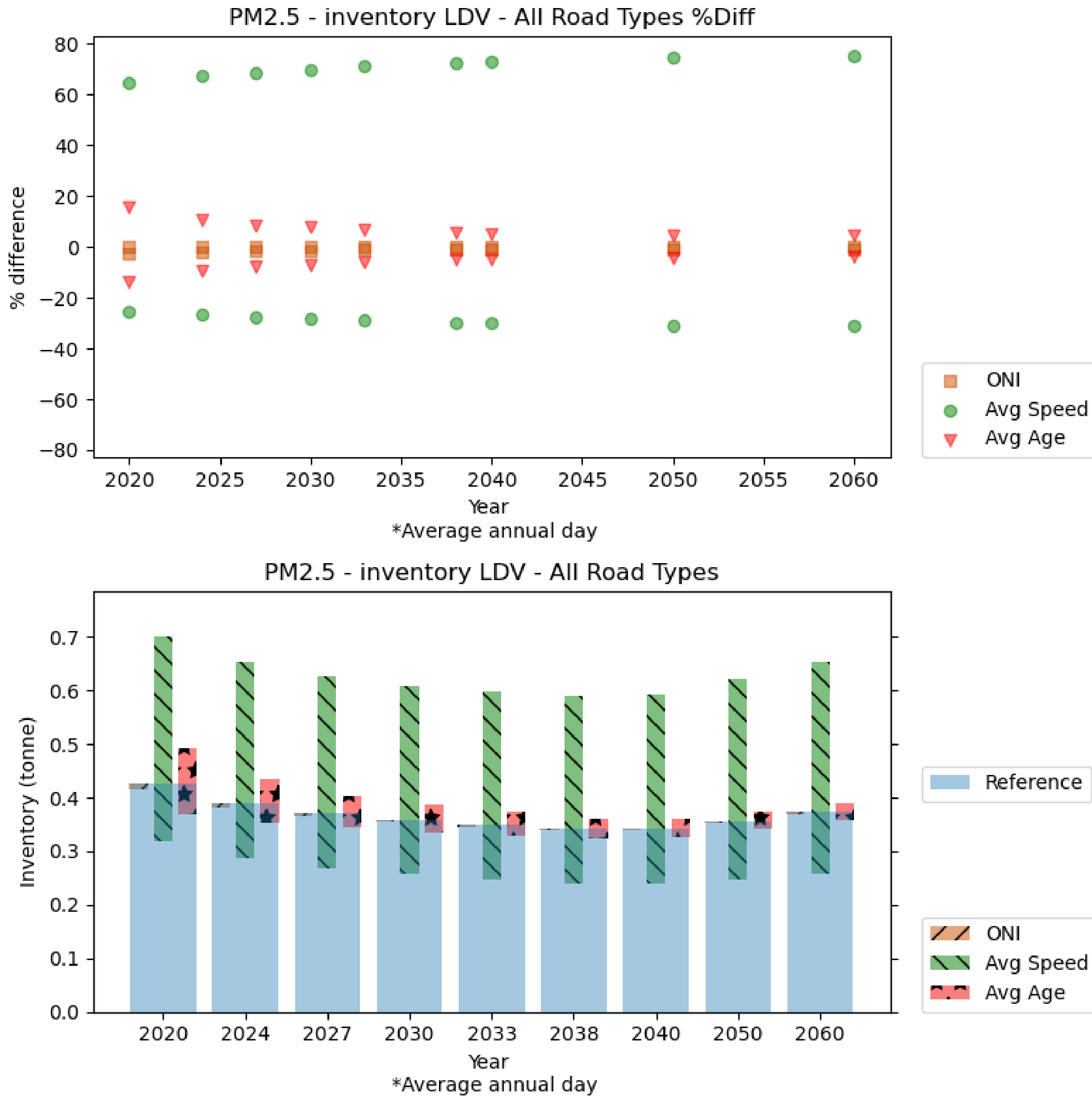


Figure 51. PM$_{2.5}$ Heavy-Duty Vehicles Inventory

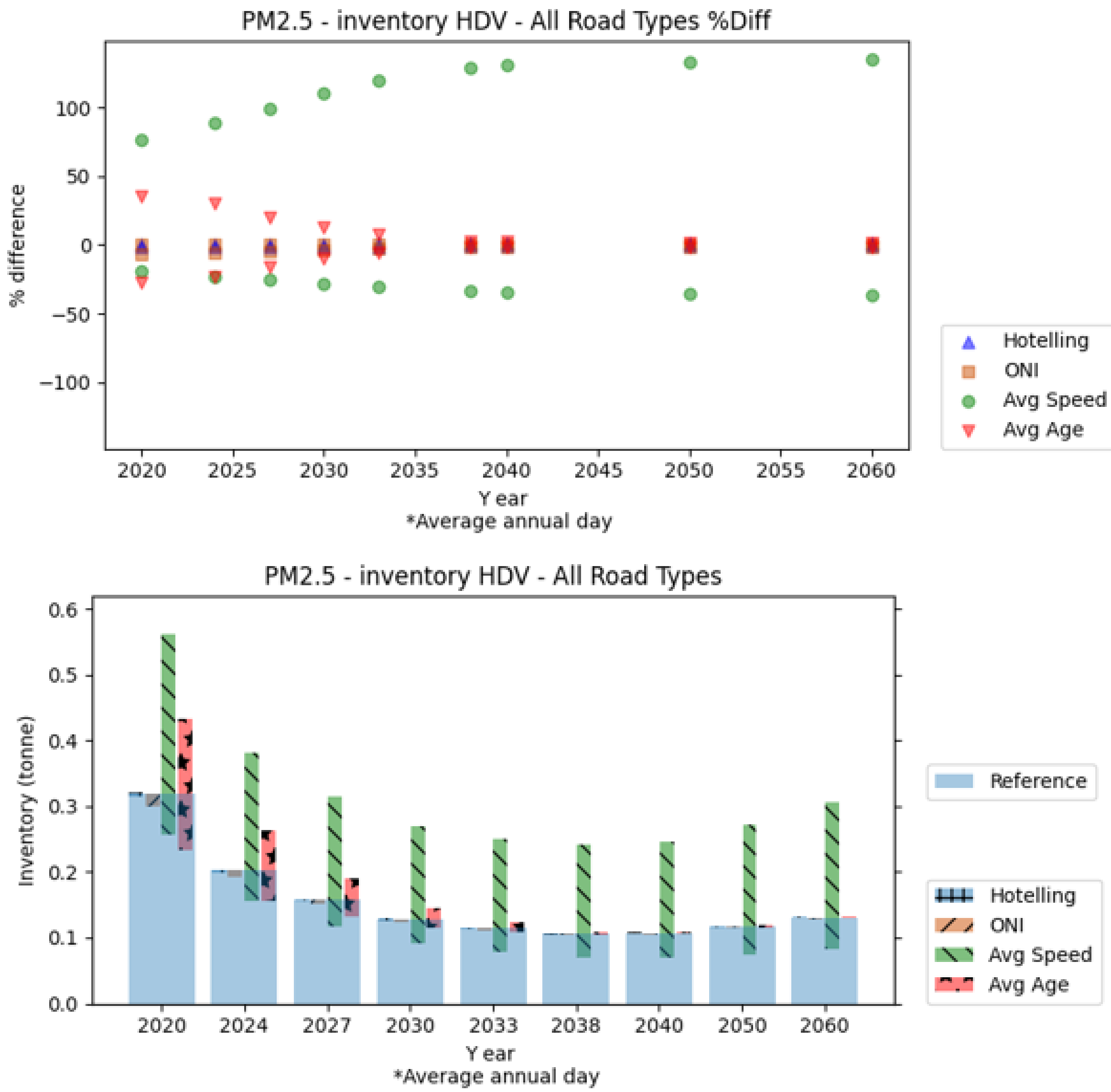
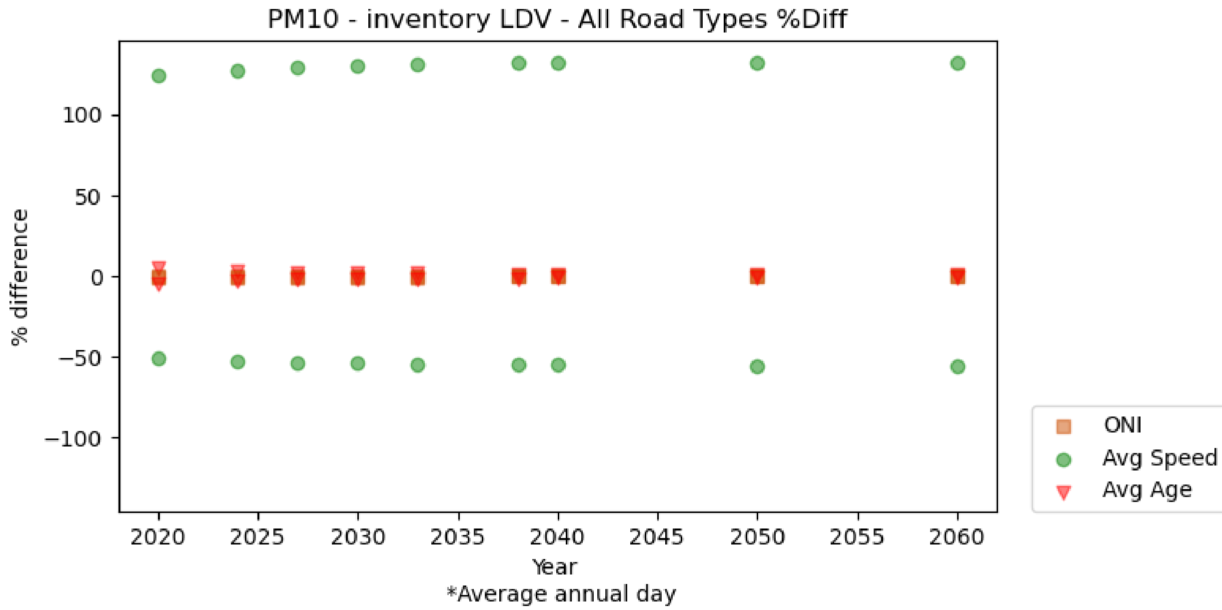


Figure 52. PM_{10} Light-Duty Vehicles Inventory



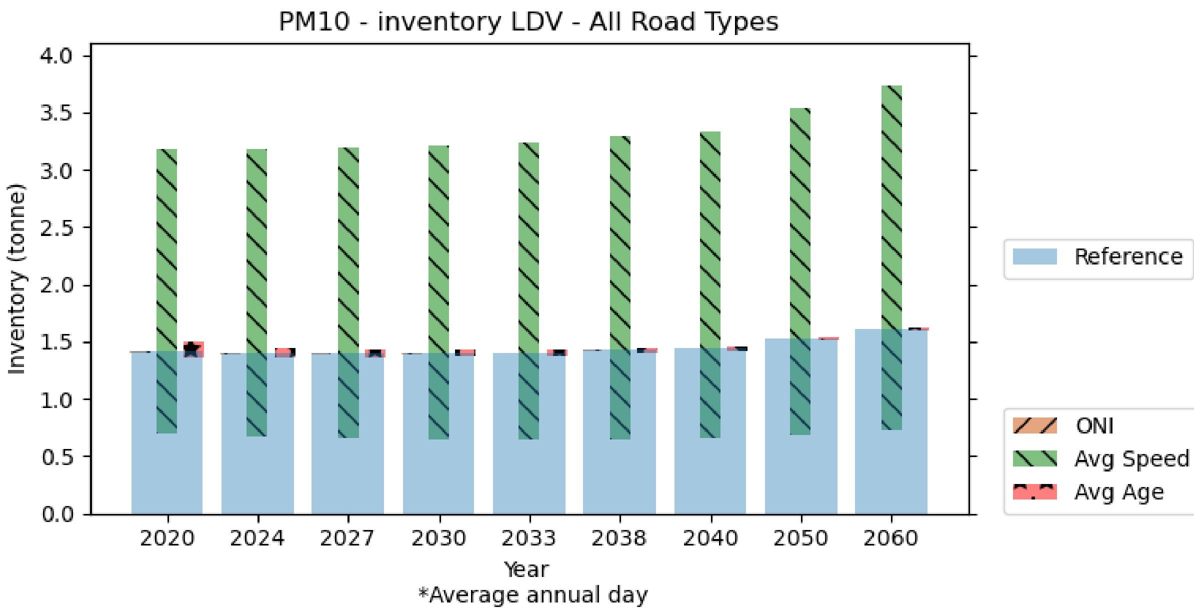
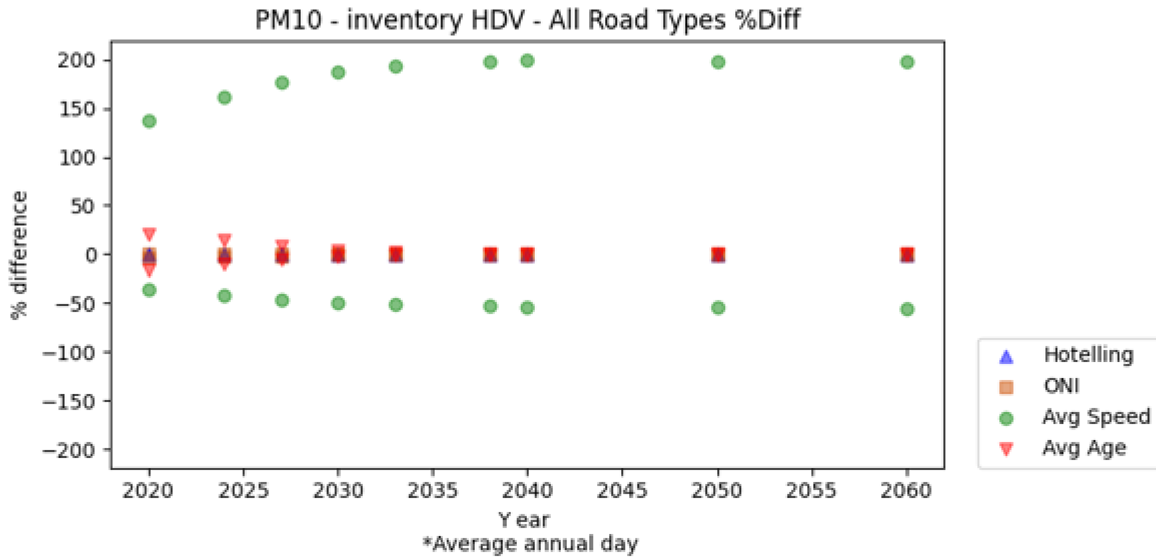


Figure 53. PM_{10} Heavy-Duty Vehicles Inventory



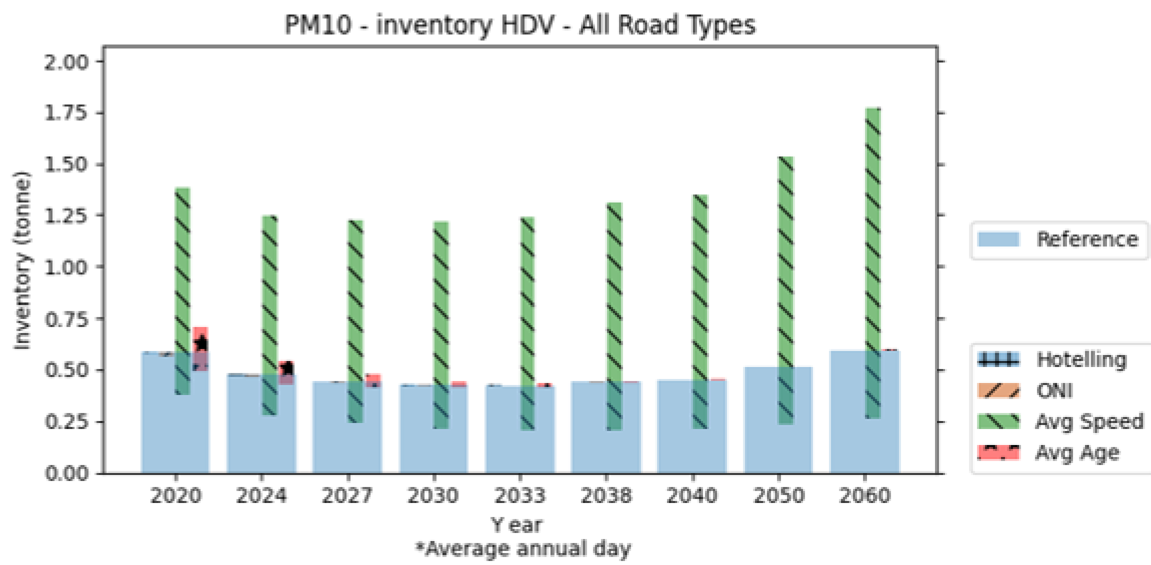


Figure 54. CO Light-Duty Vehicles Inventory

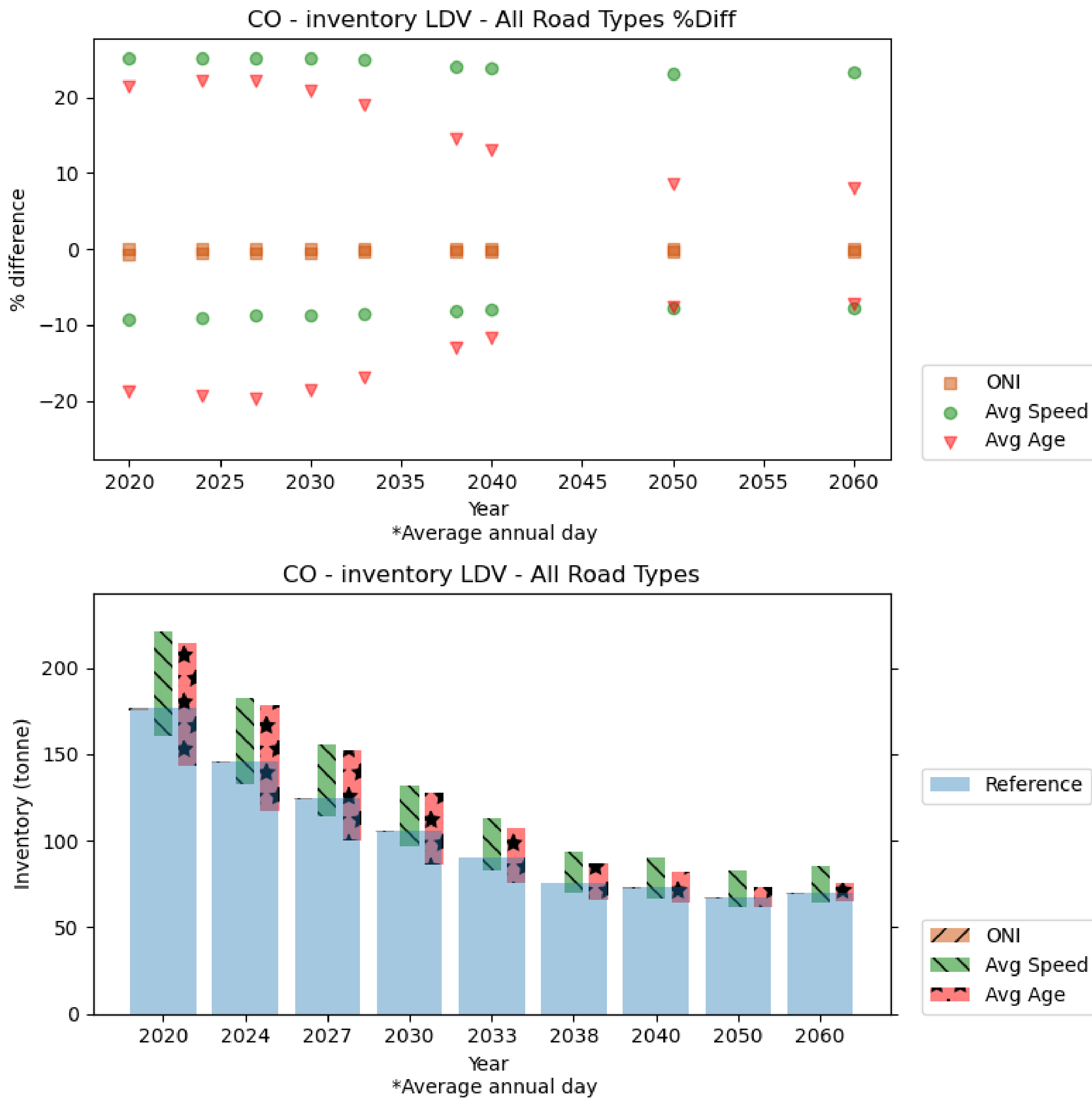
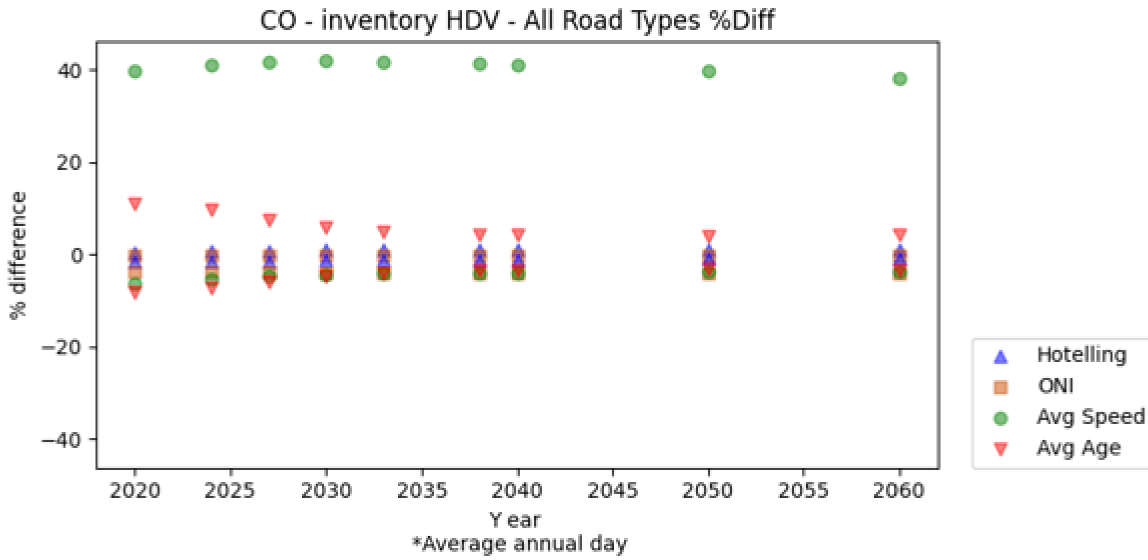


Figure 55. CO Heavy-Duty Vehicles Inventory



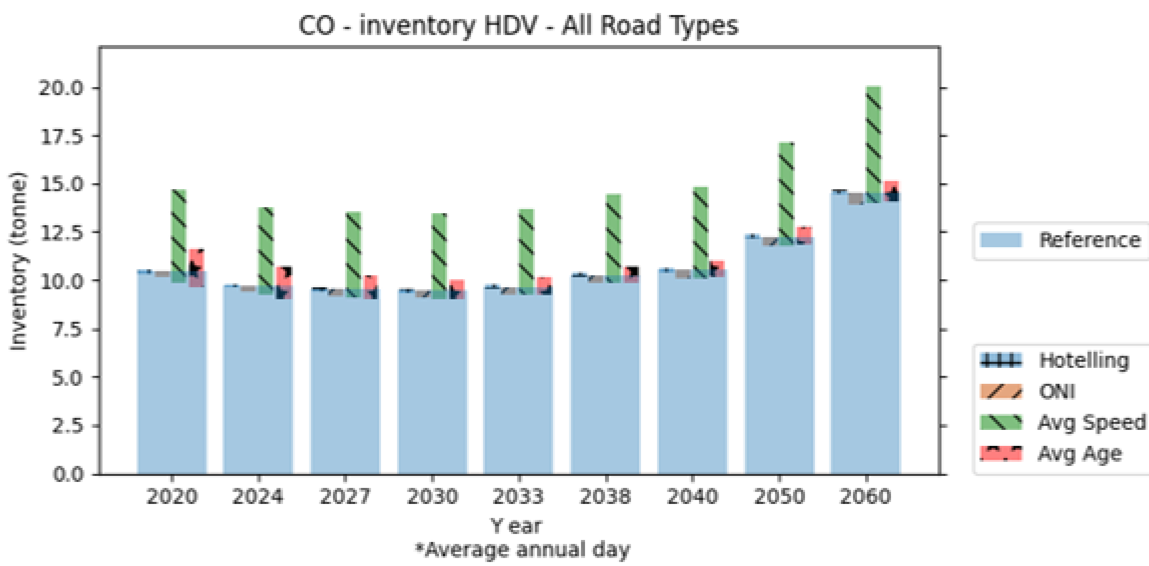


Figure 56. CO_2eq Light-Duty Vehicles Inventory

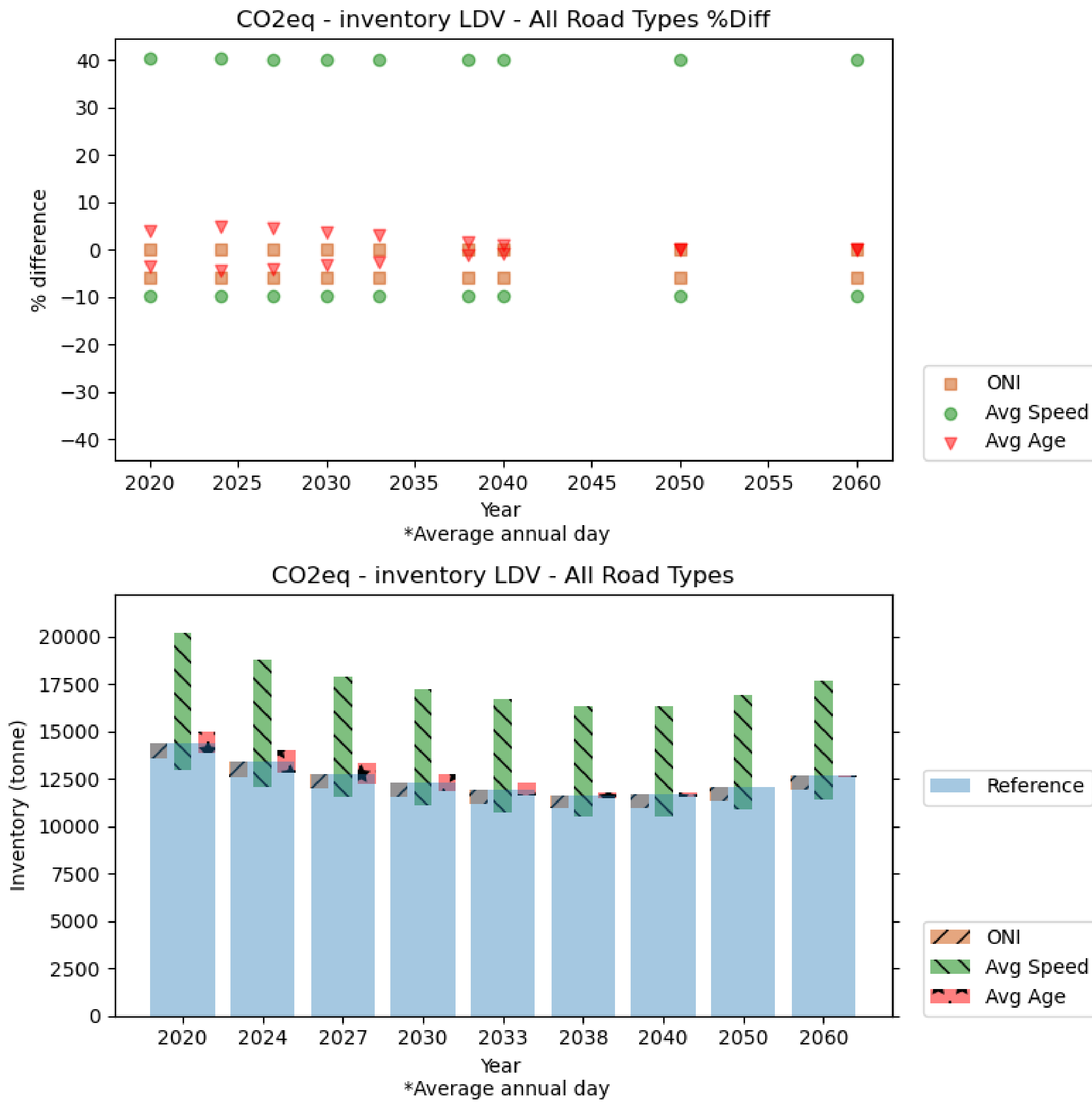
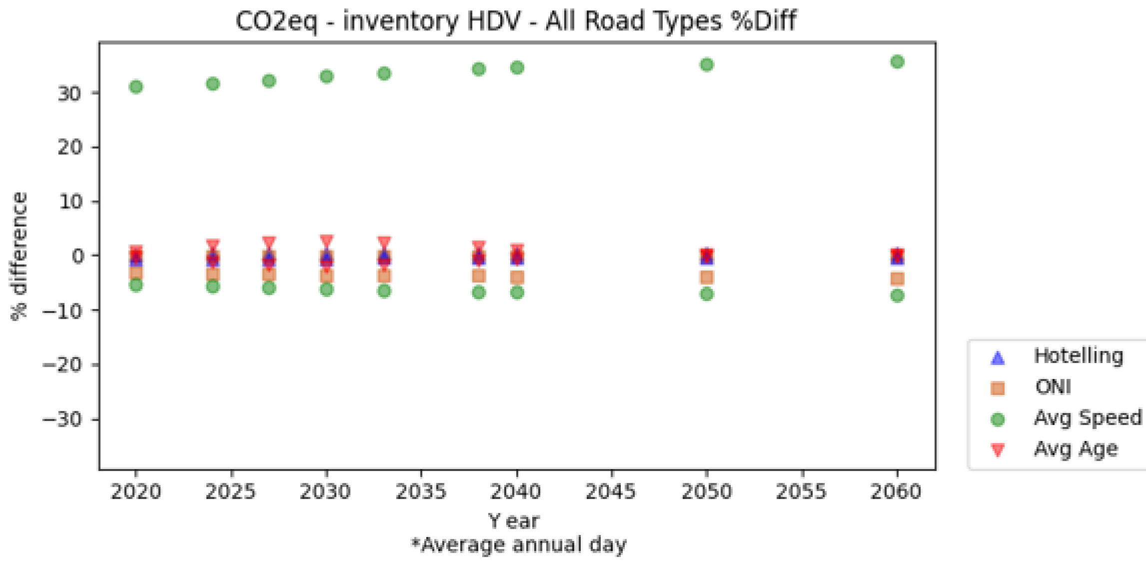
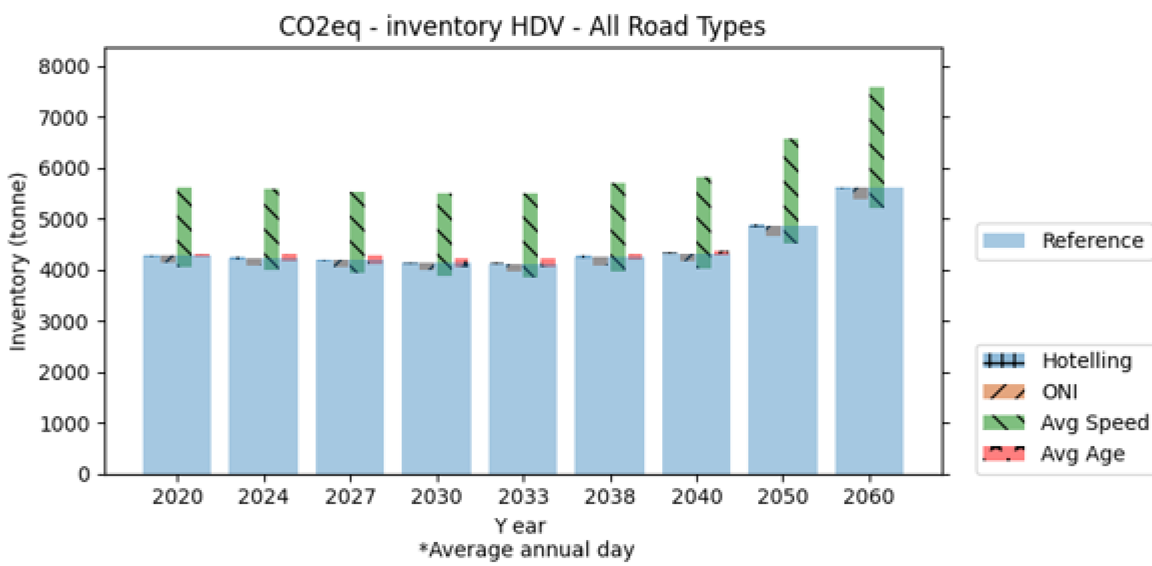


Figure 57. CO_2eq Heavy-Duty Vehicles Inventory





Off-Network, Unrestricted, Restricted

Figure 58. VOC Off-Network Inventory

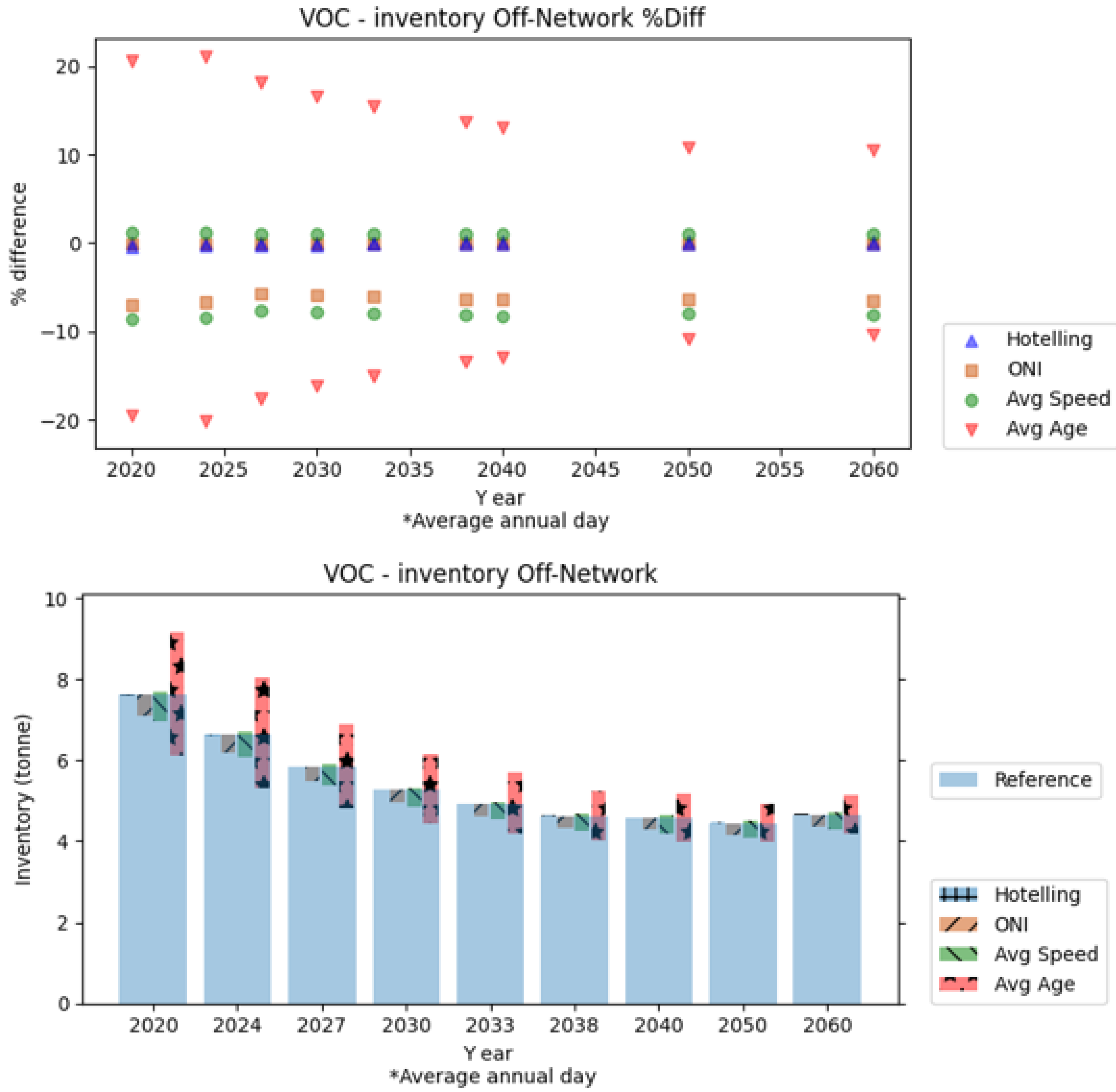


Figure 59. VOC Unrestricted Inventory

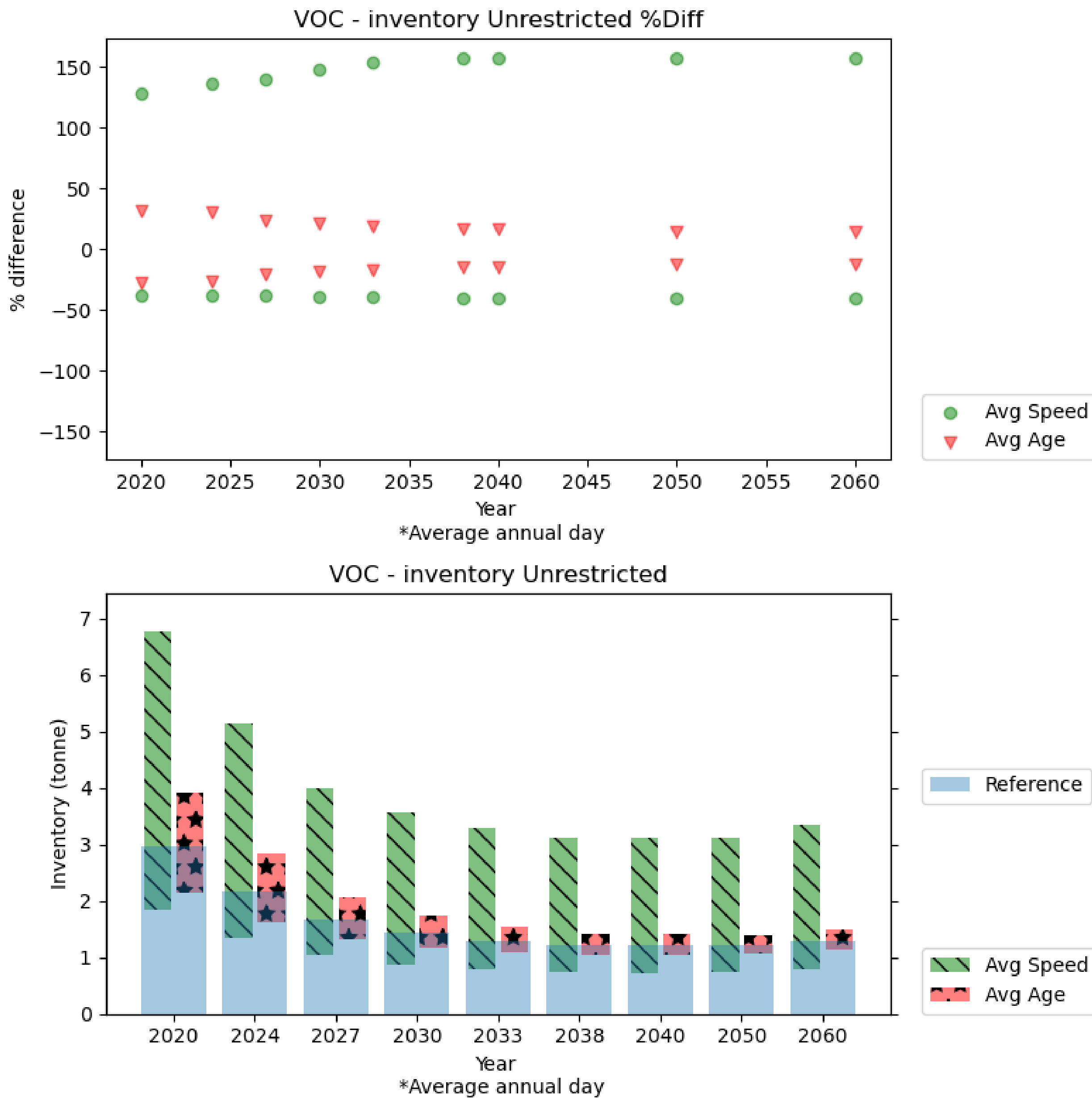
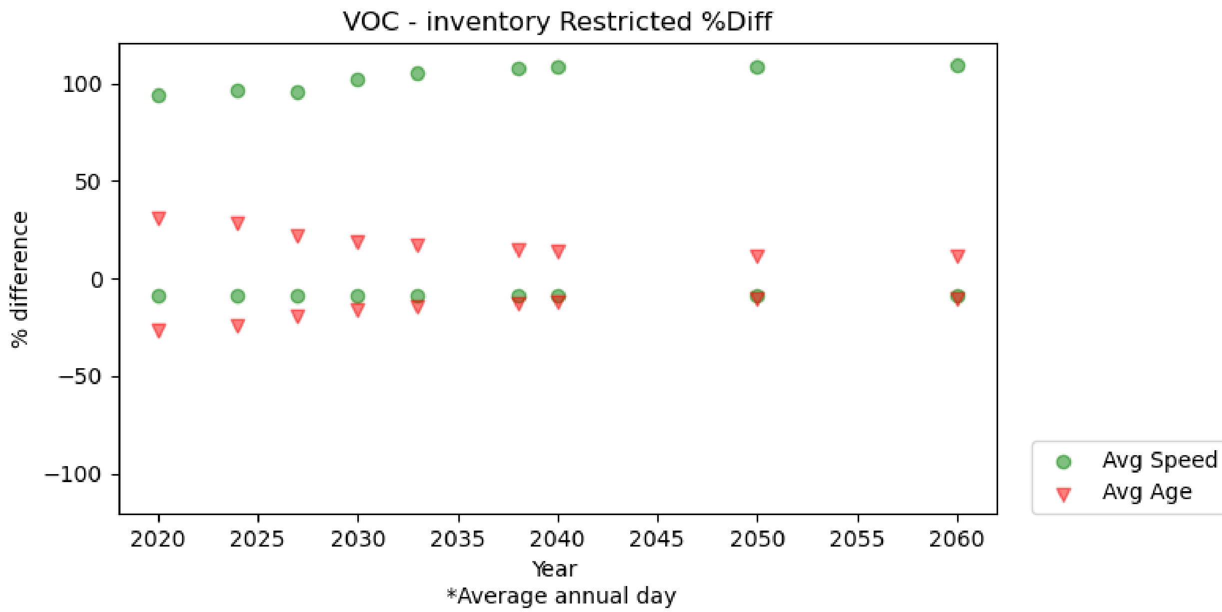


Figure 60. VOC Restricted Inventory



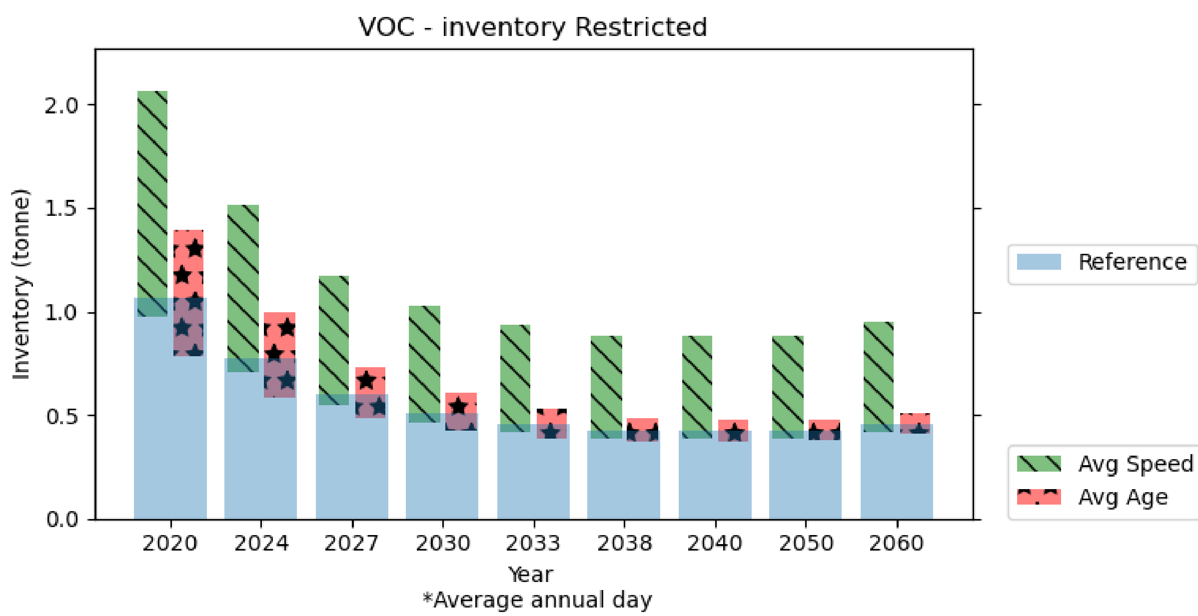


Figure 61. NO_x Off-Network Inventory

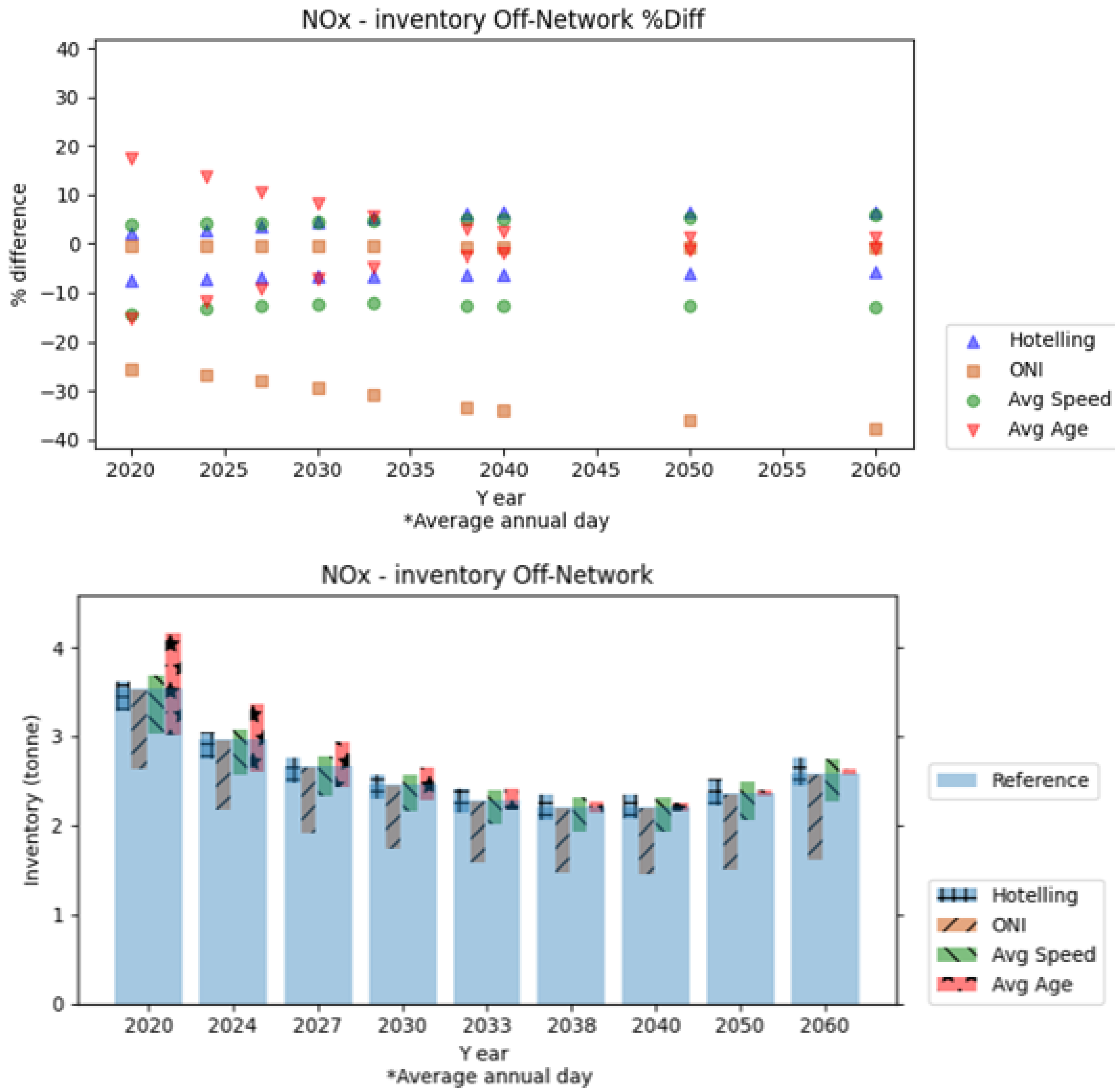


Figure 62. NO_x Unrestricted Inventory

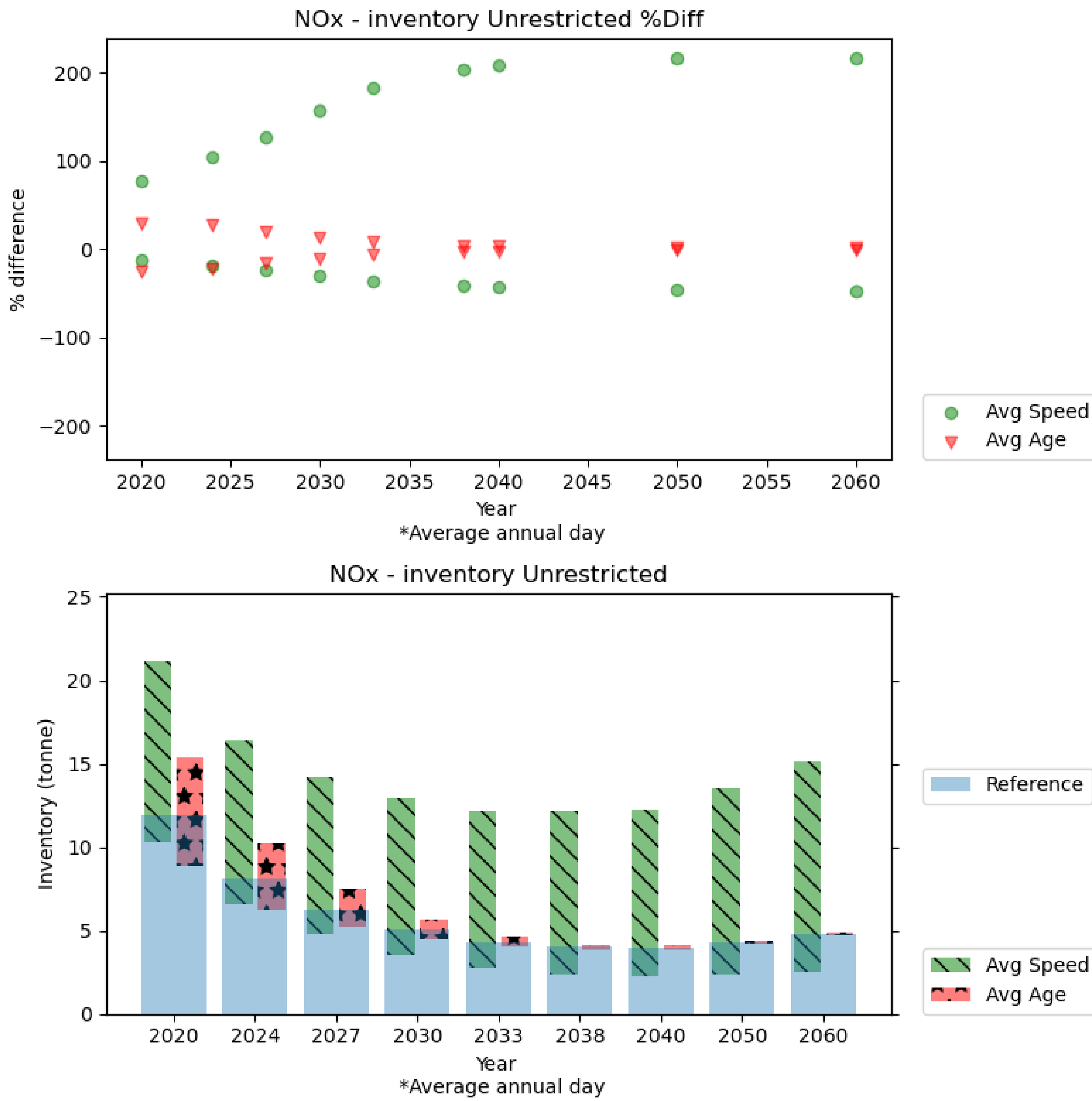


Figure 63. NO_x Restricted Inventory

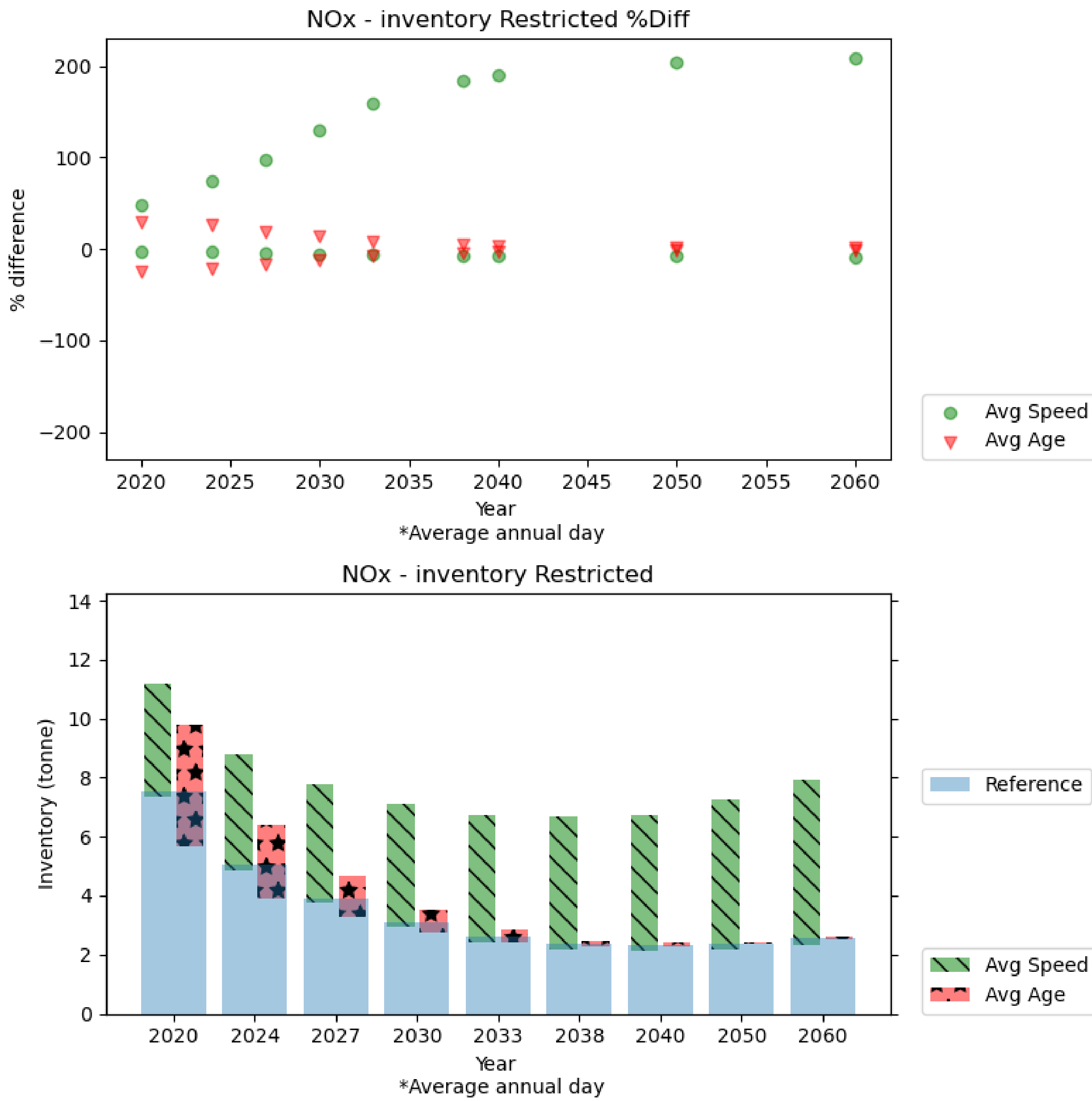
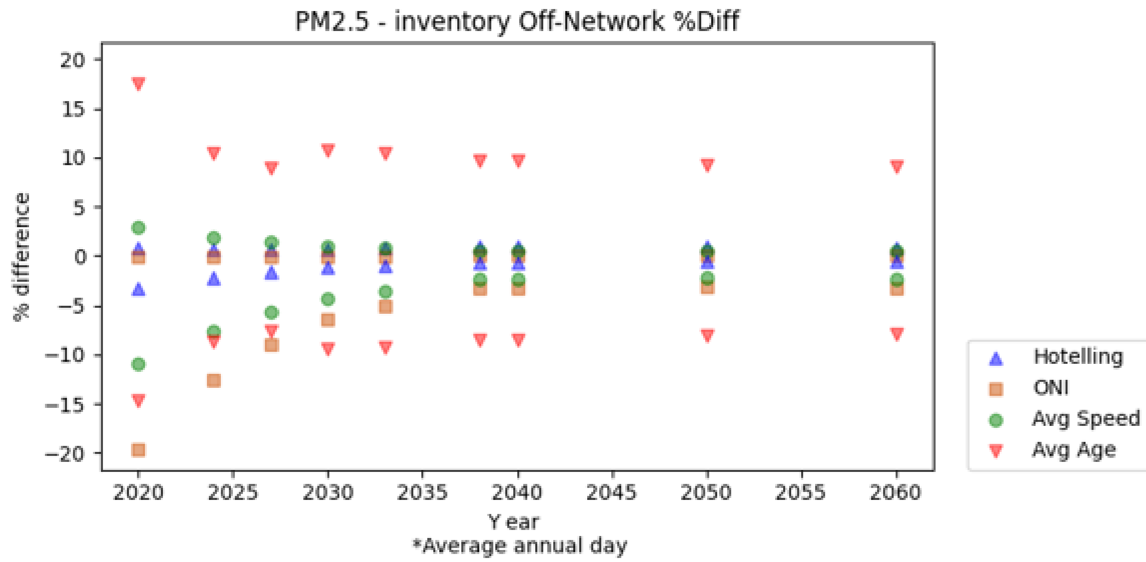


Figure 64. $PM_{2.5}$ Off-Network Inventory



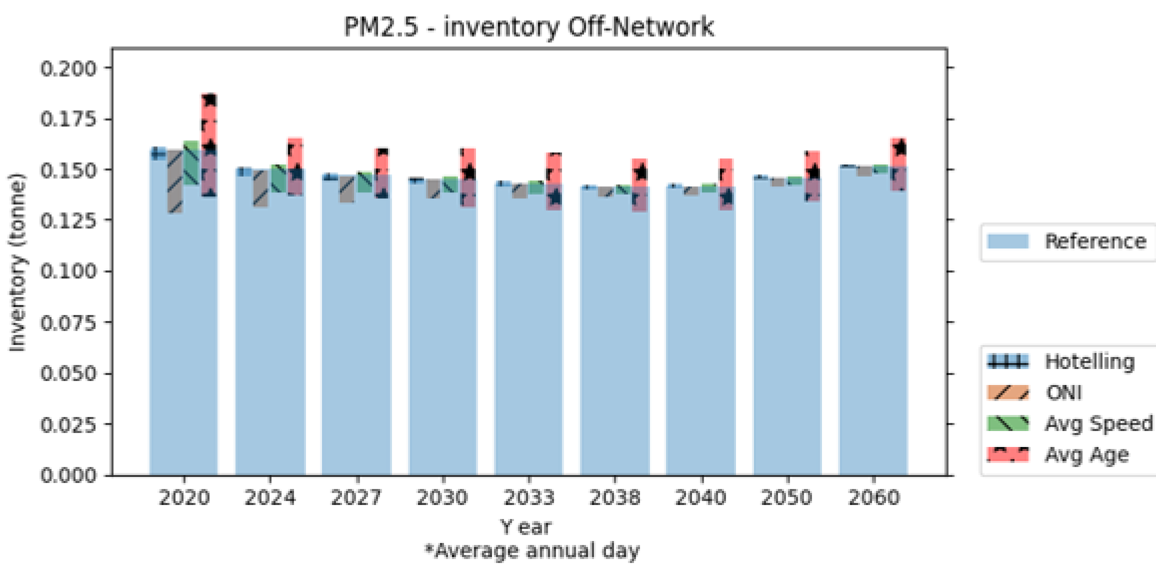
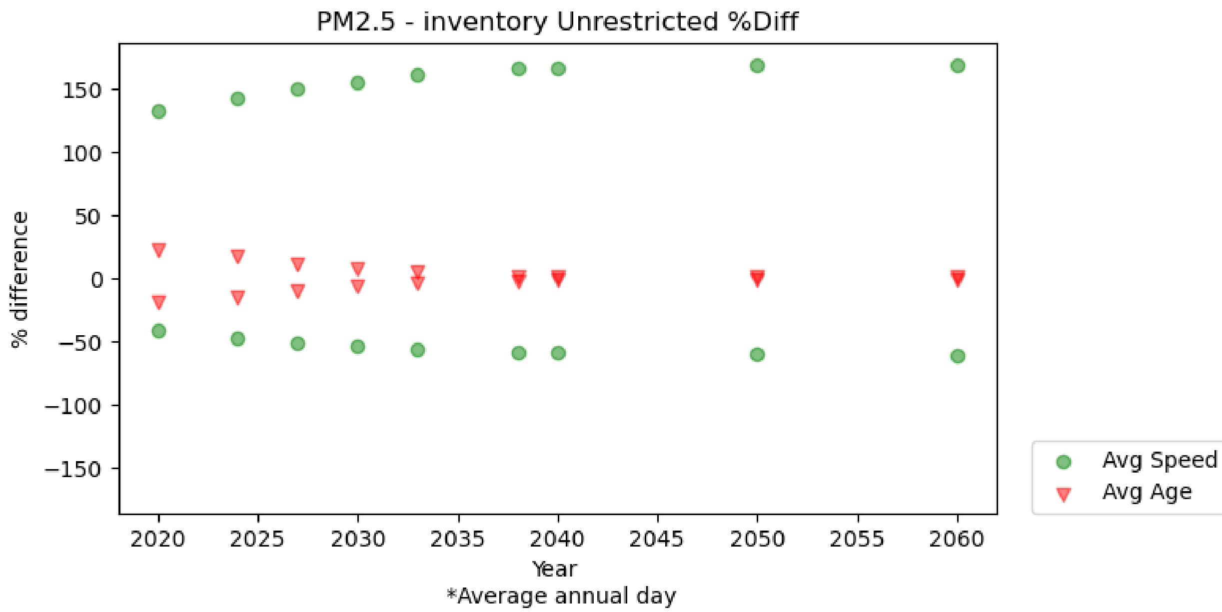


Figure 65. $PM_{2.5}$ Unrestricted Inventory



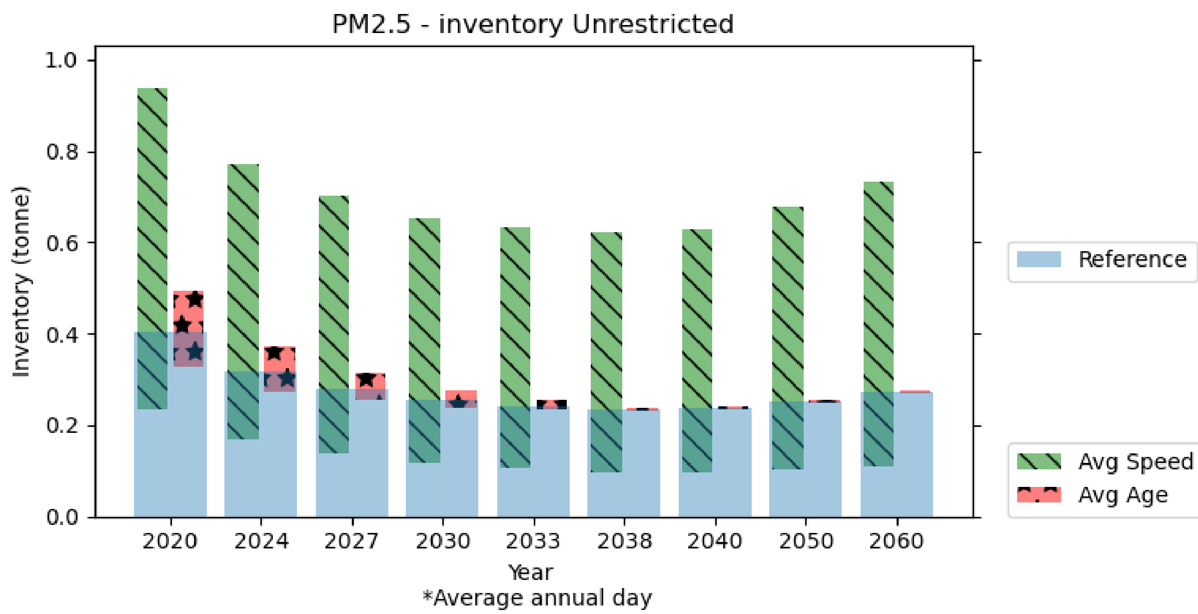


Figure 66. $PM_{2.5}$ Restricted Inventory

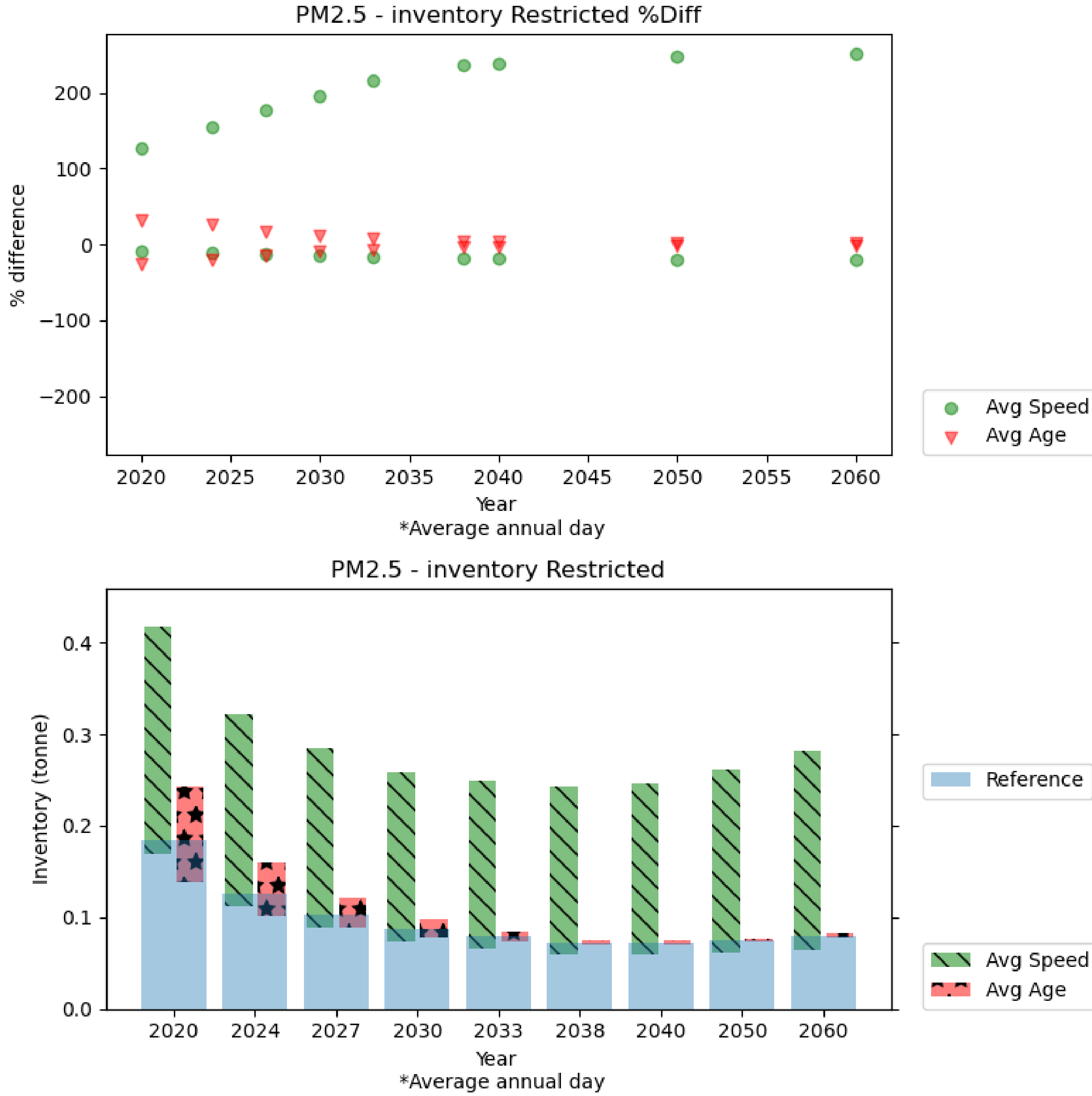


Figure 67. PM_{10} Off-Network Inventory

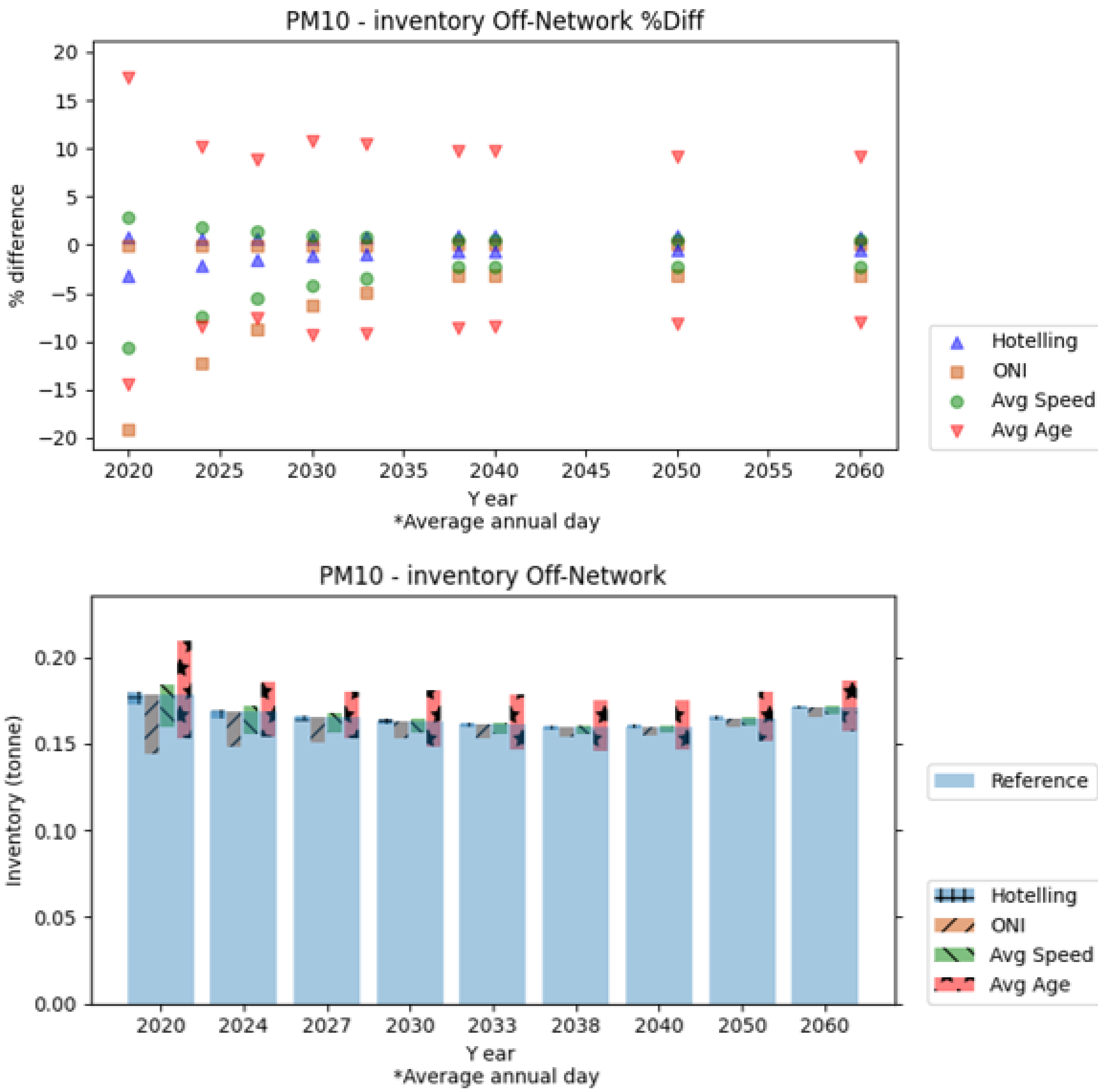


Figure 68. PM_{10} Unrestricted Inventory

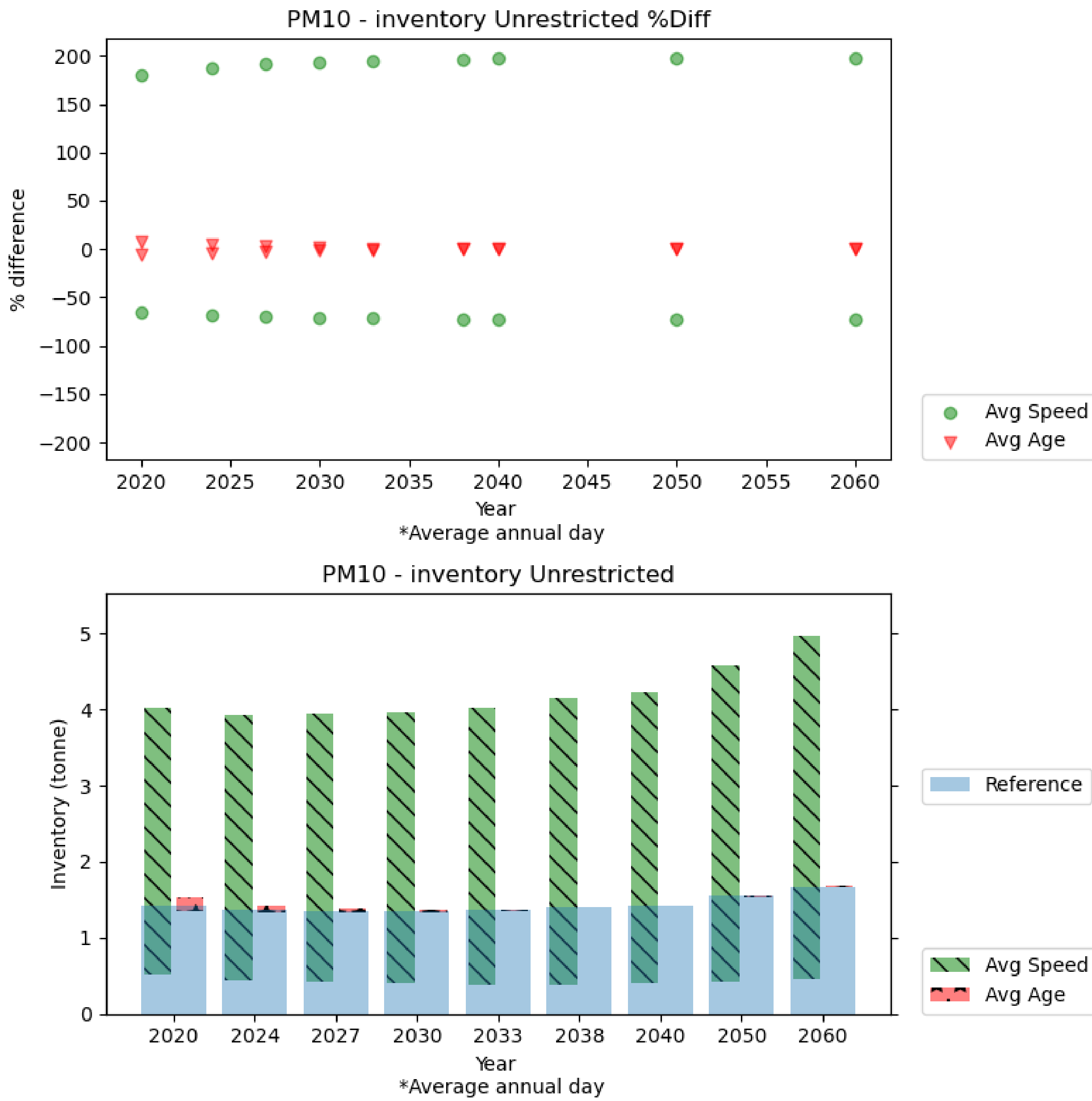


Figure 69. PM_{10} Restricted Inventory

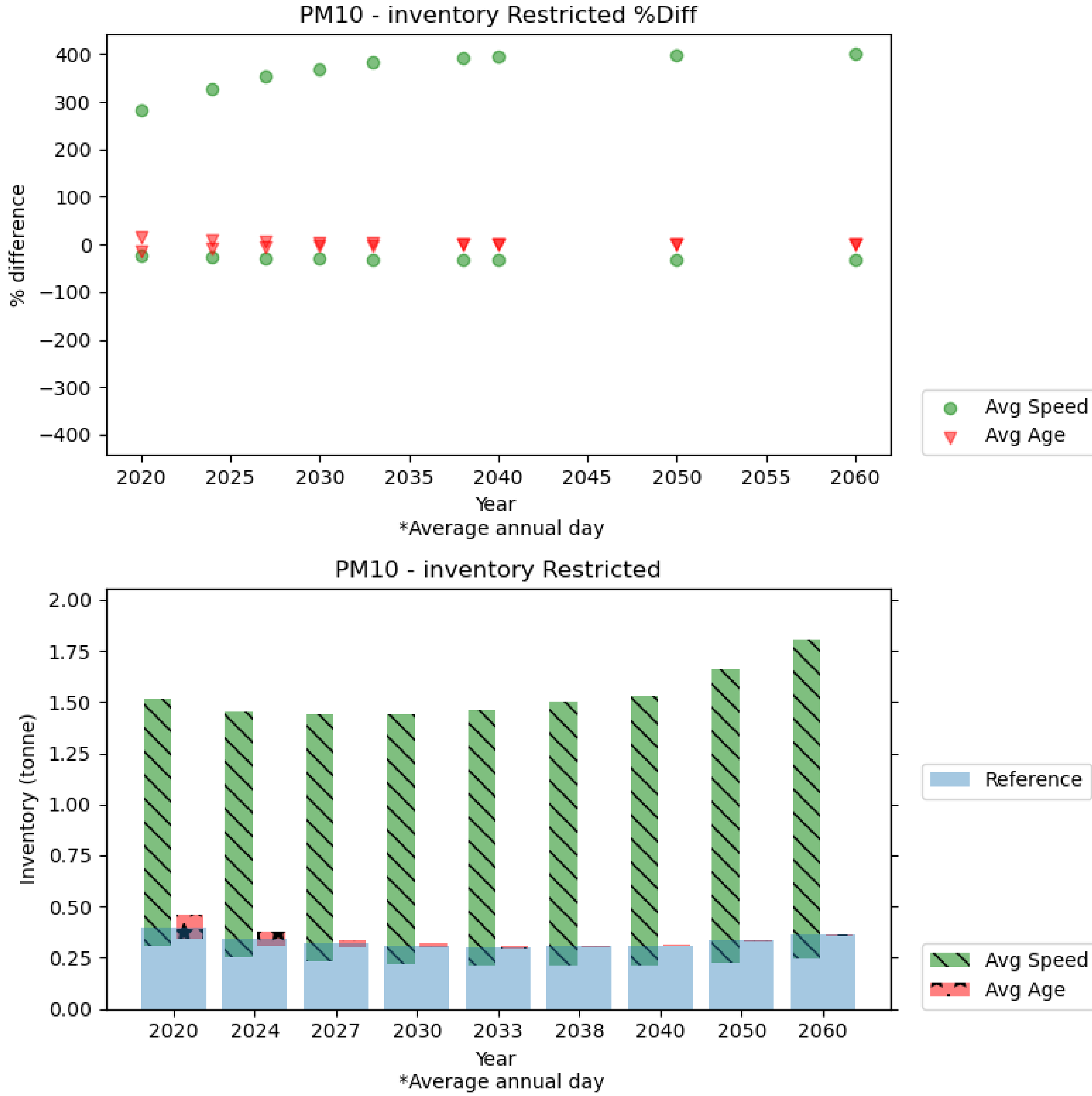
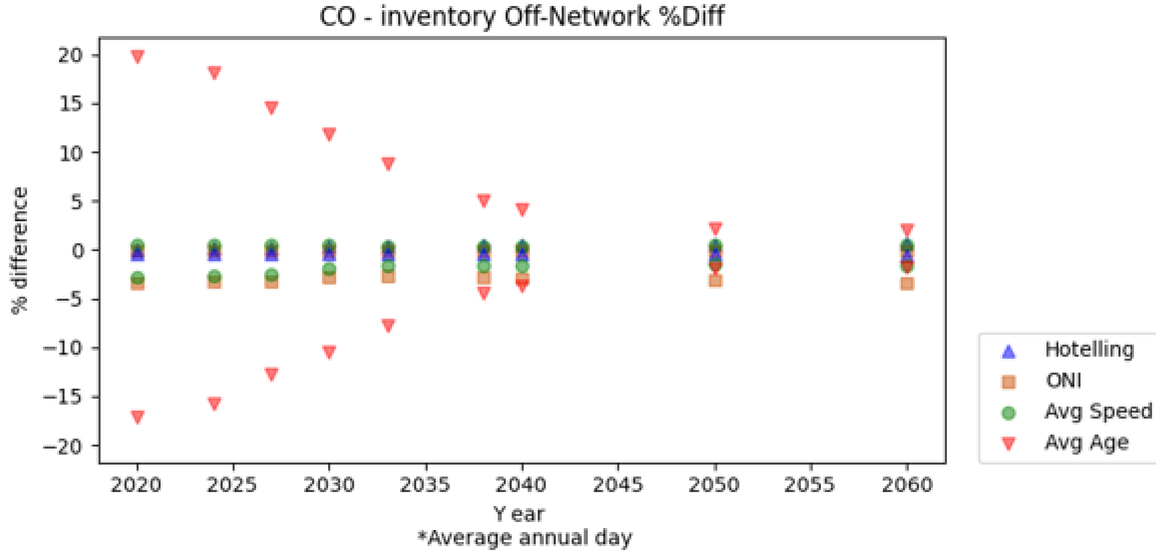


Figure 70. CO Off-Network Inventory



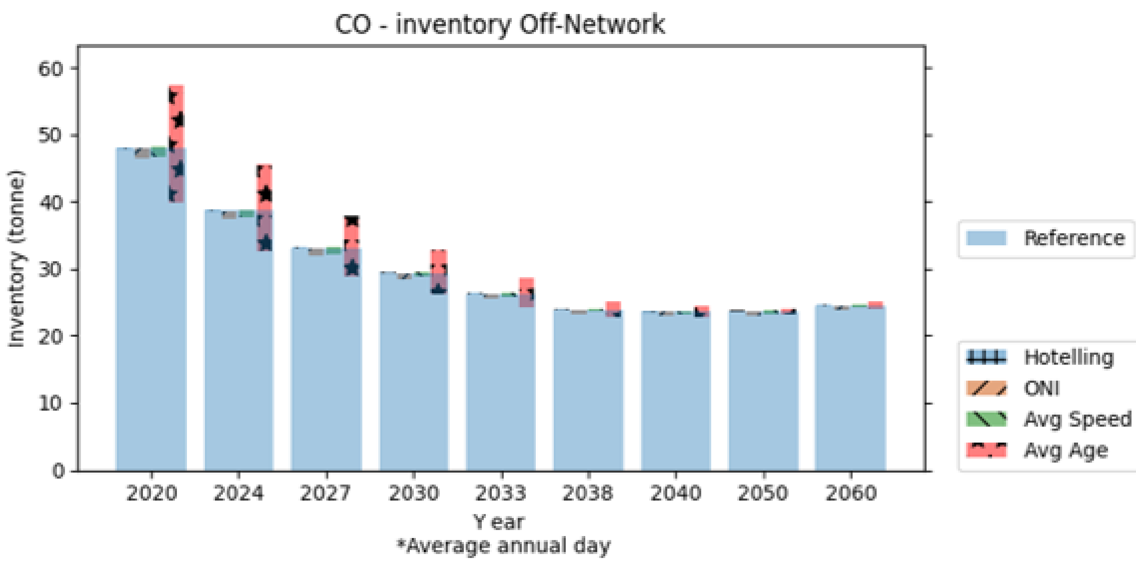


Figure 71. CO Unrestricted Inventory

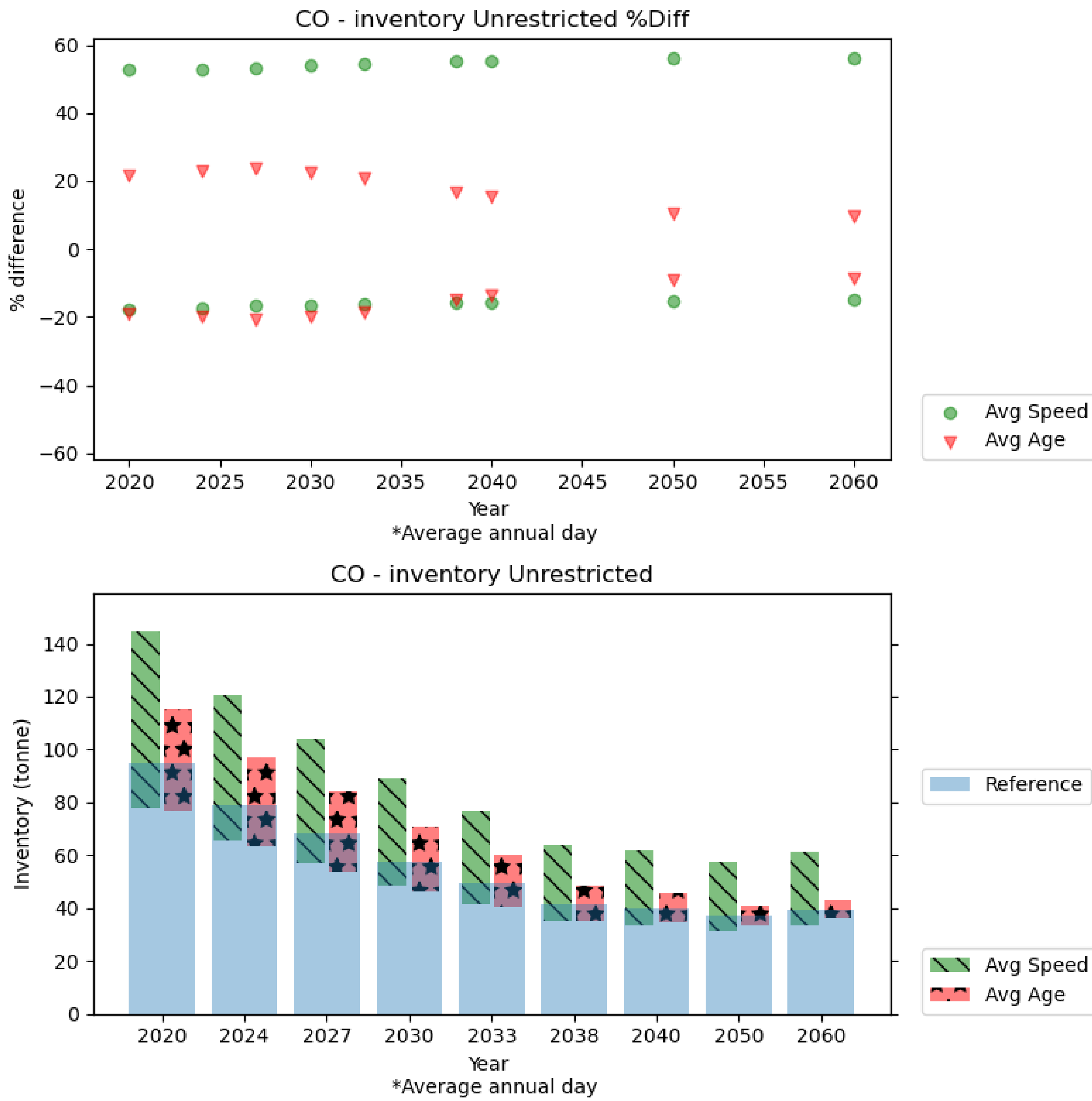


Figure 72. CO Restricted Inventory

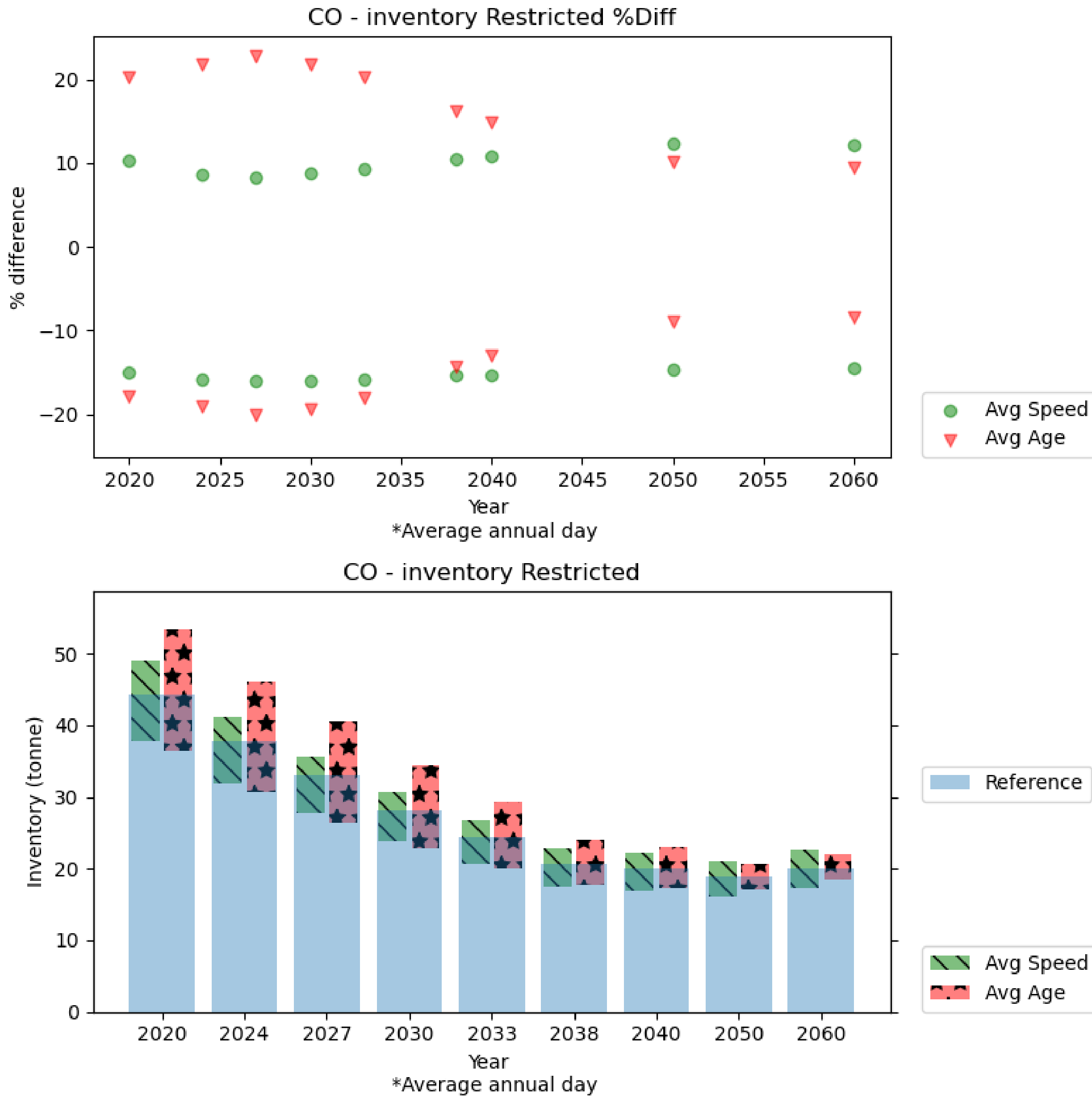


Figure 73. CO_2eq Off-Network Inventory

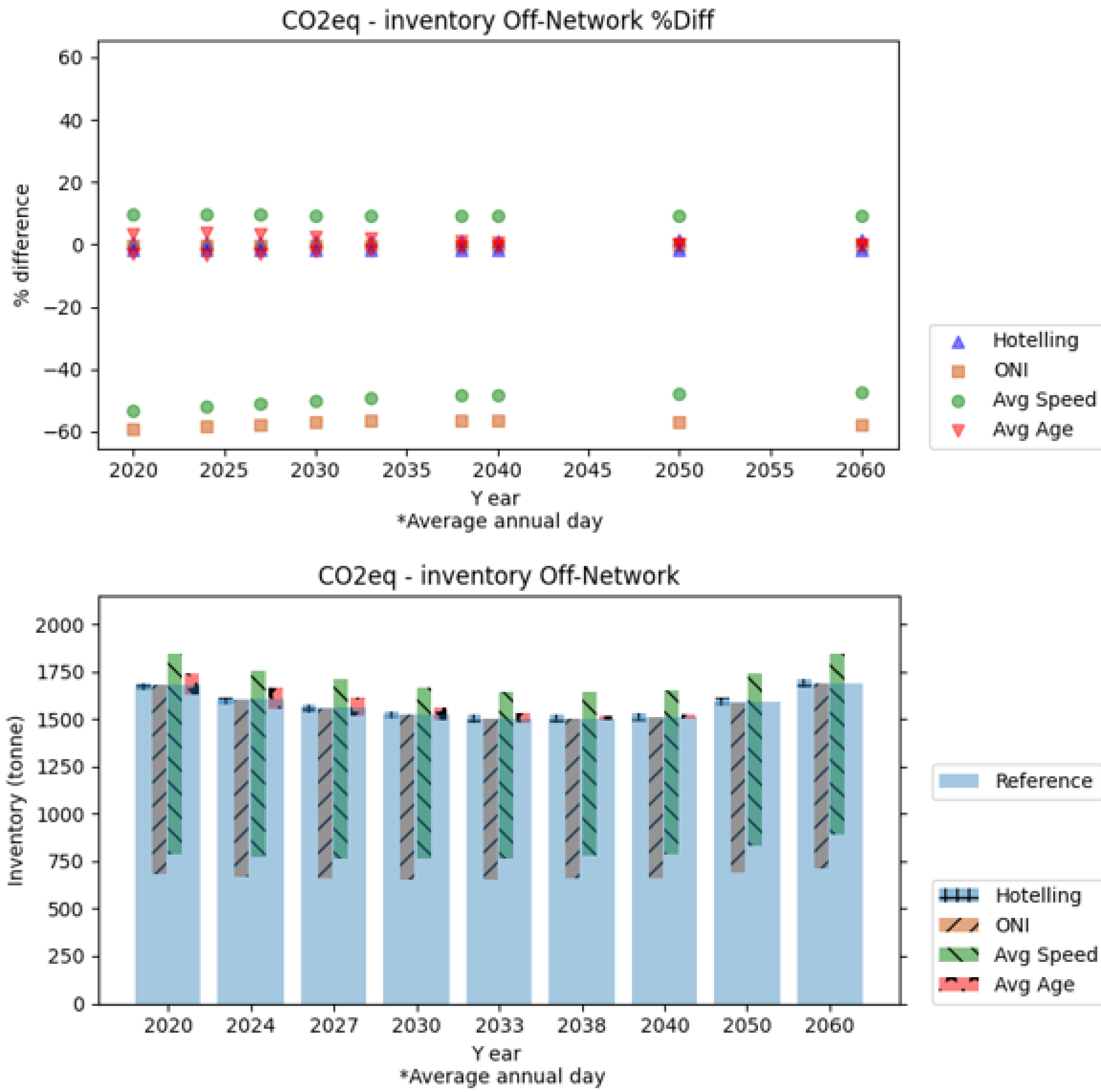


Figure 74. CO_2eq Unrestricted Inventory

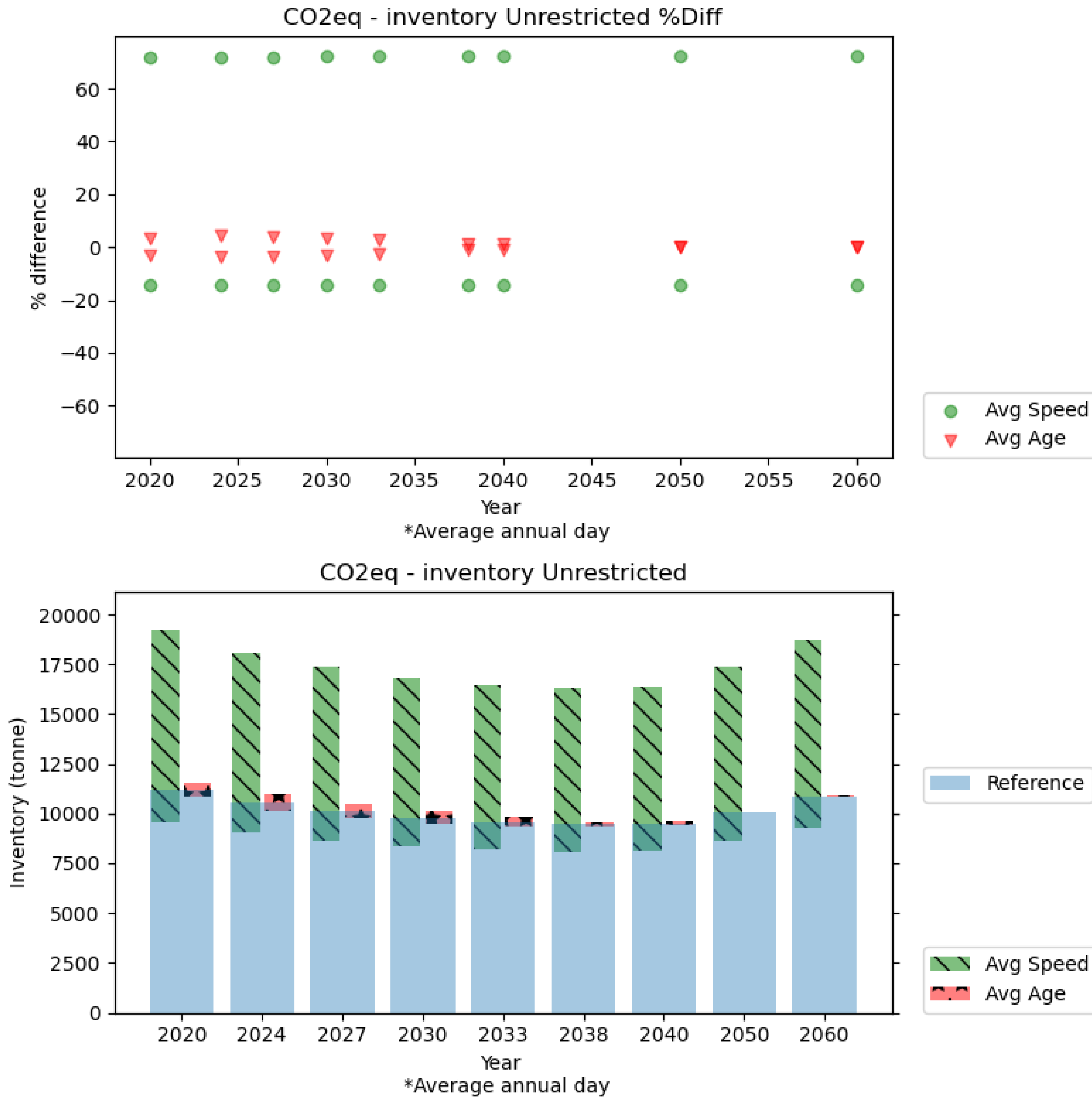
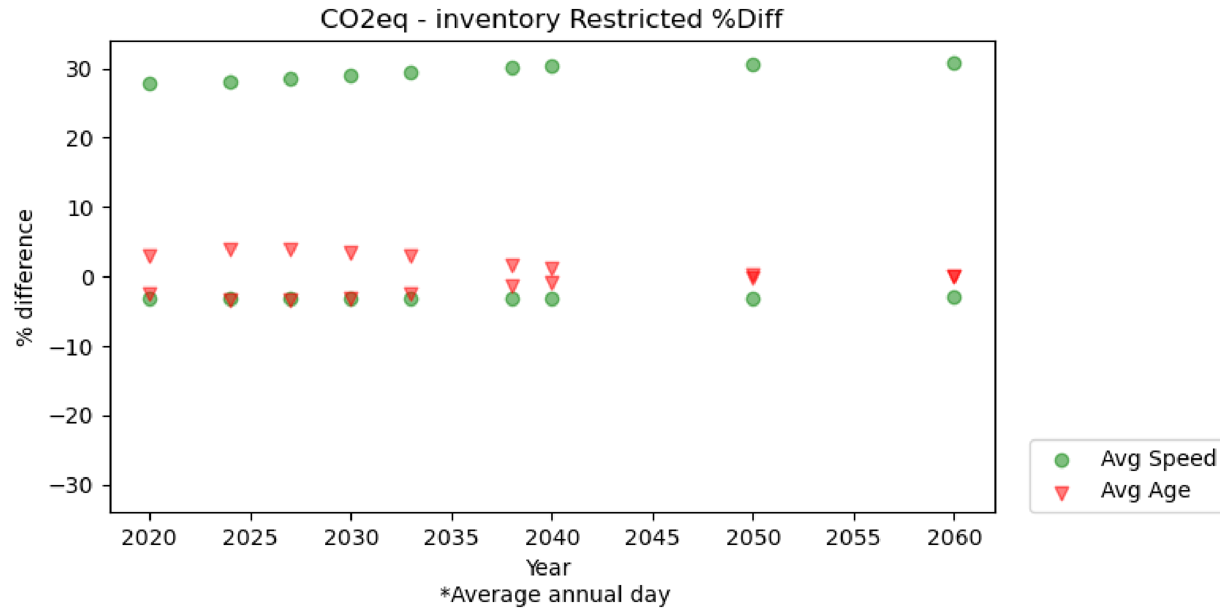
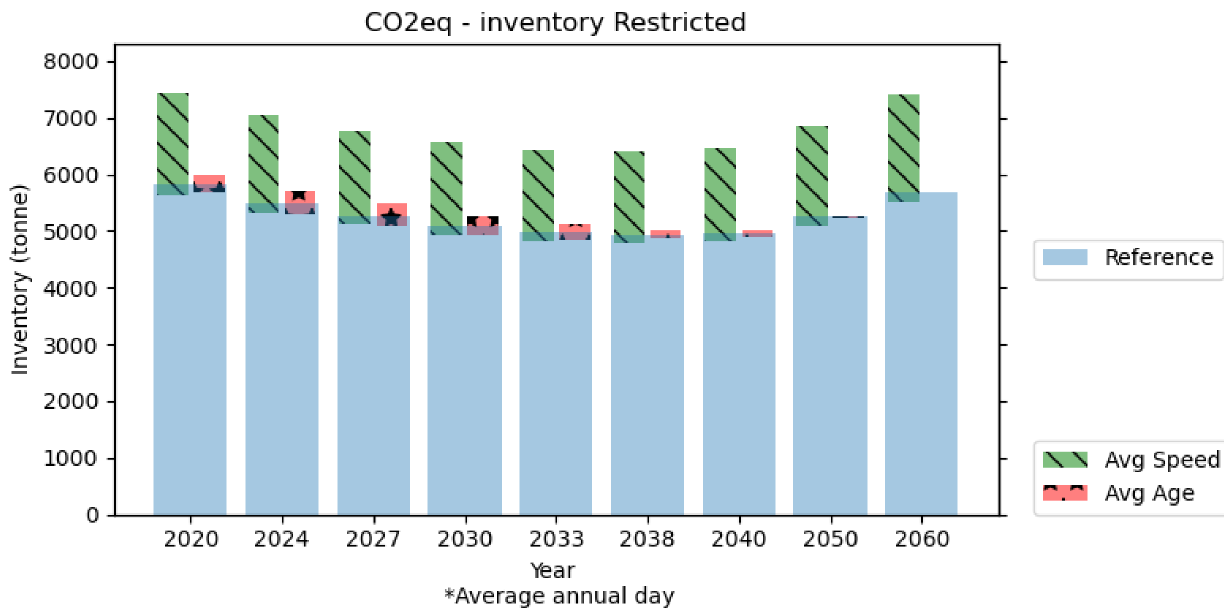


Figure 75. CO_2eq Restricted Inventory





Urban & Rural

Figure 76. VOC Urban Inventory

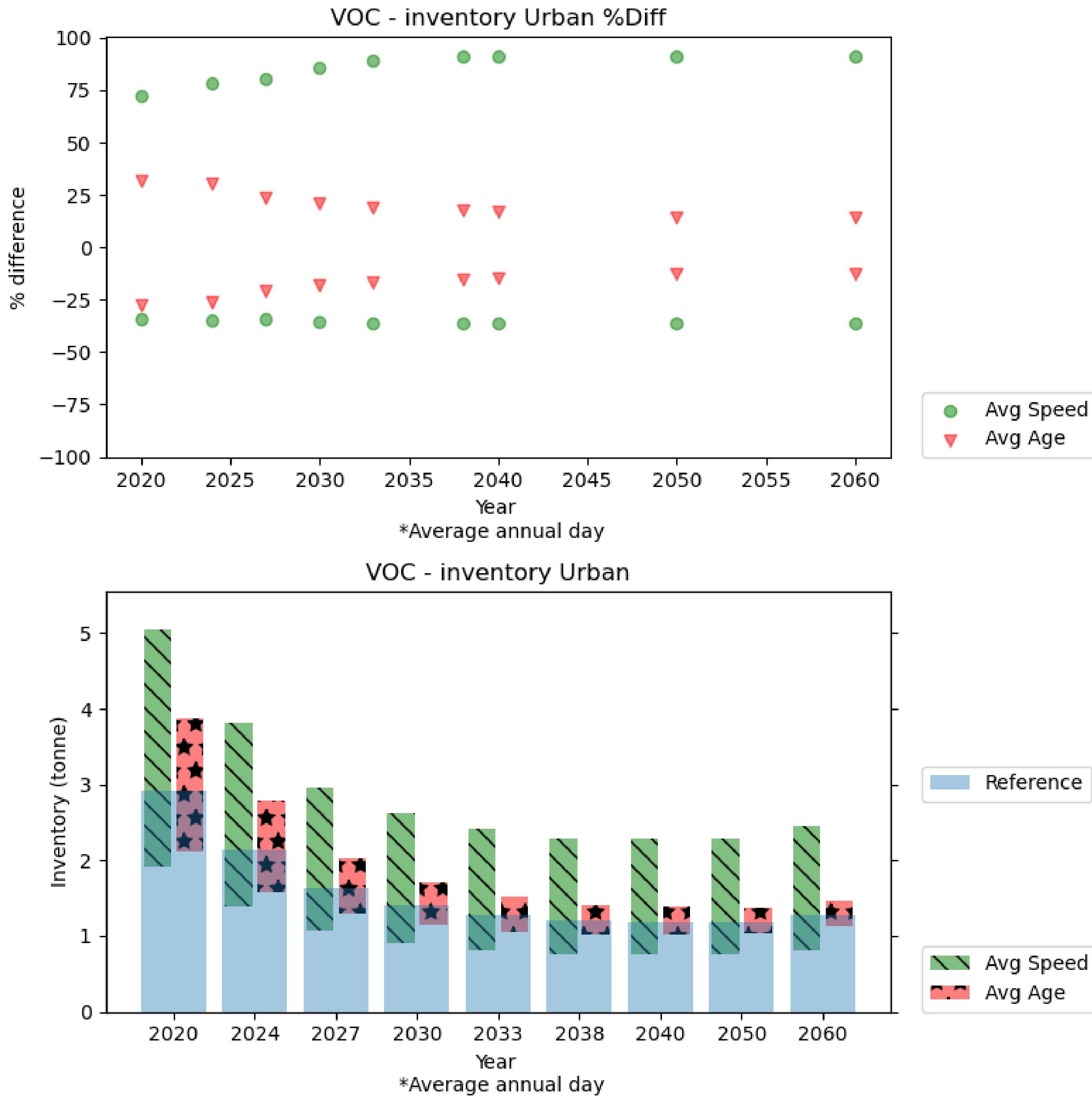
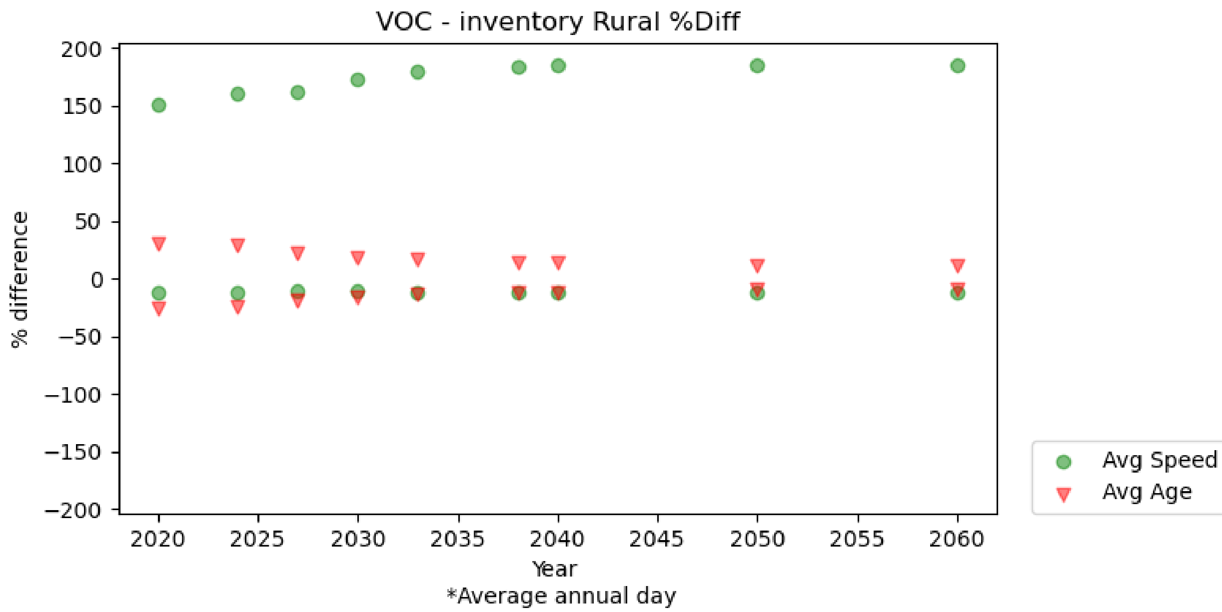


Figure 77. VOC Rural Inventory



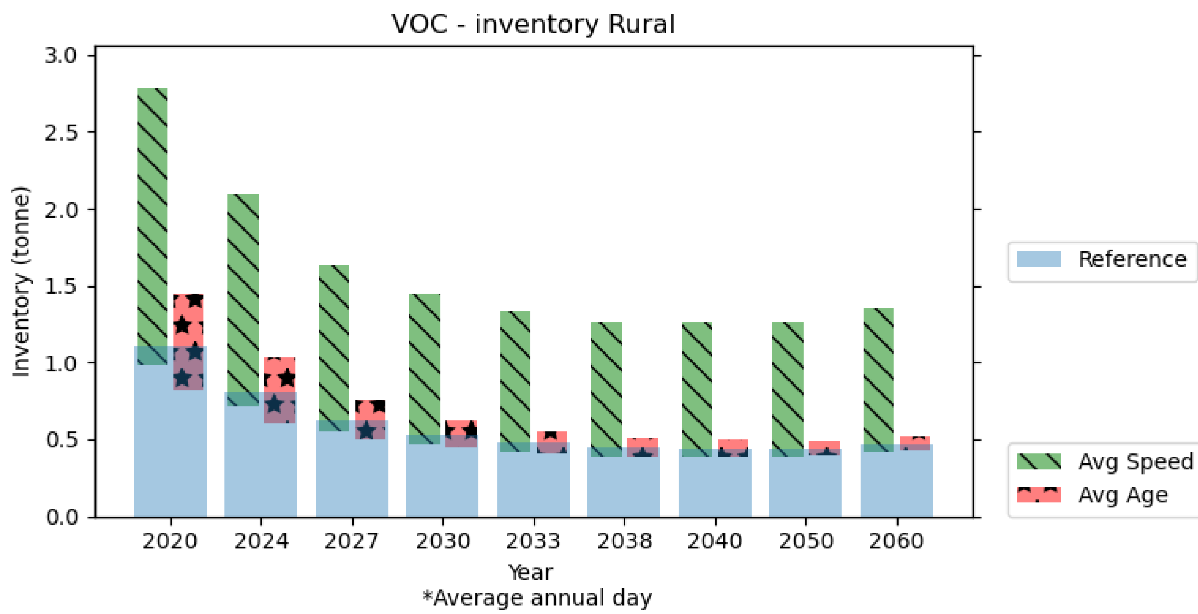


Figure 78. NO_x Urban Inventory

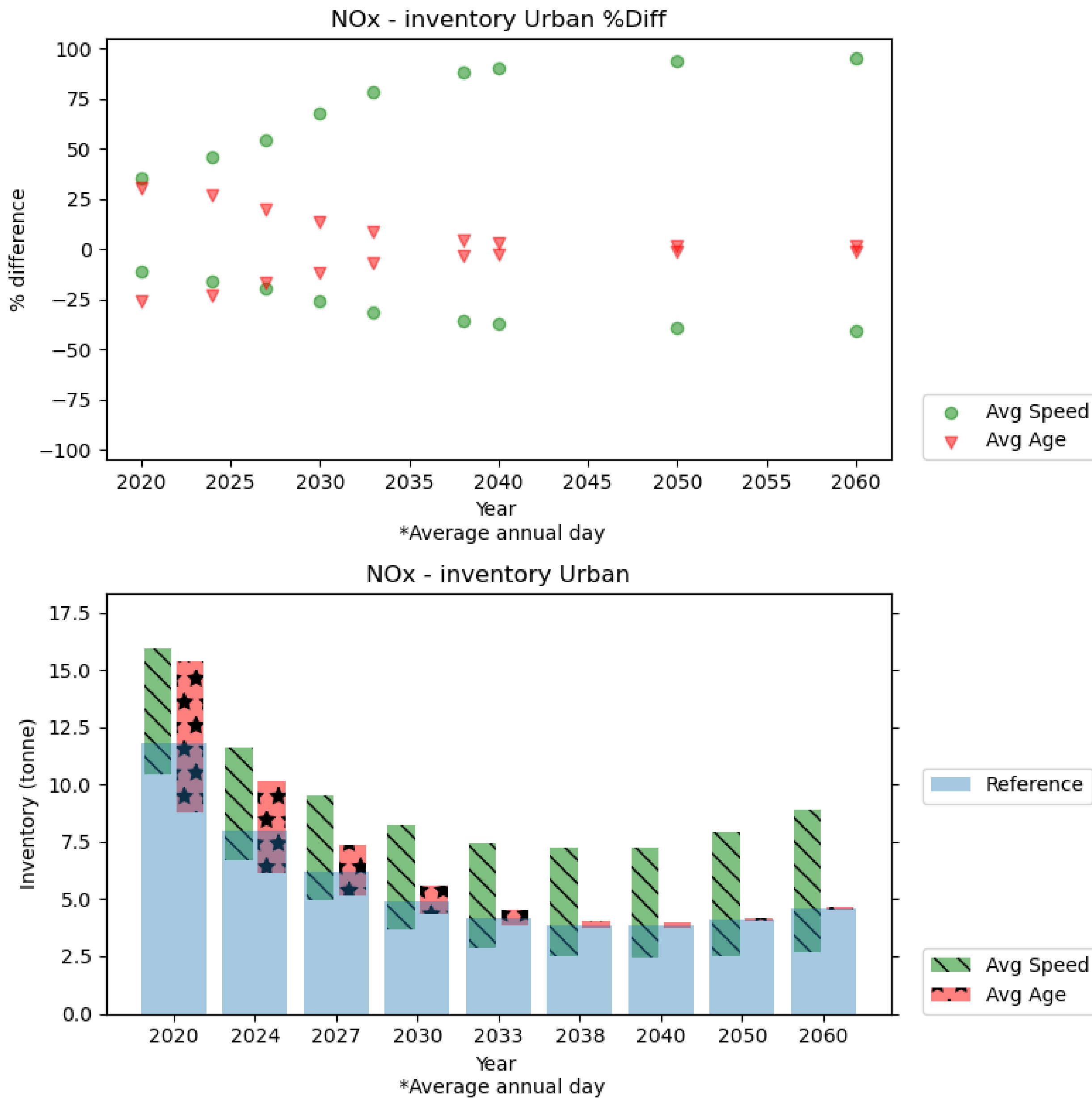


Figure 79. NO_x Rural Inventory

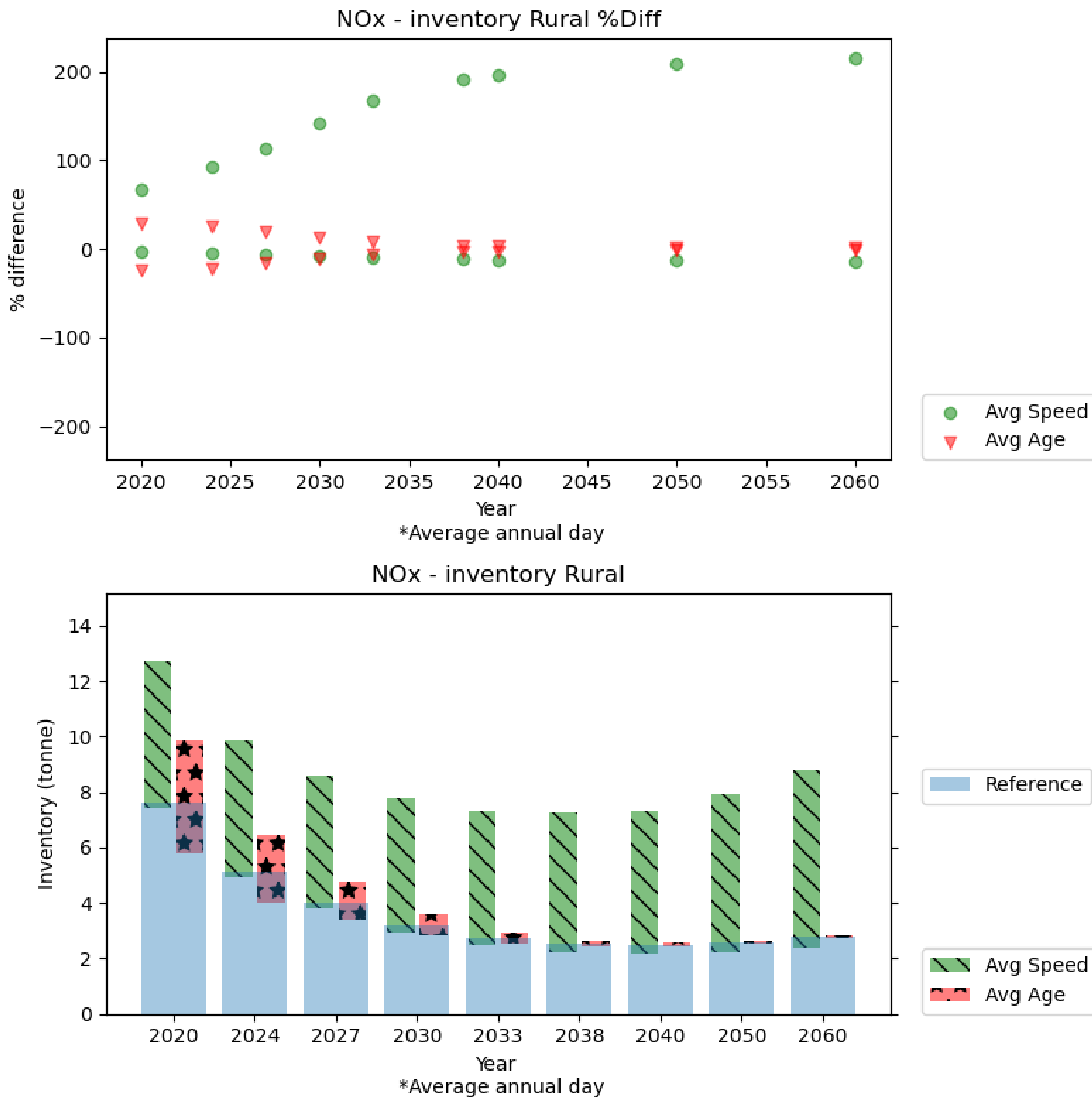
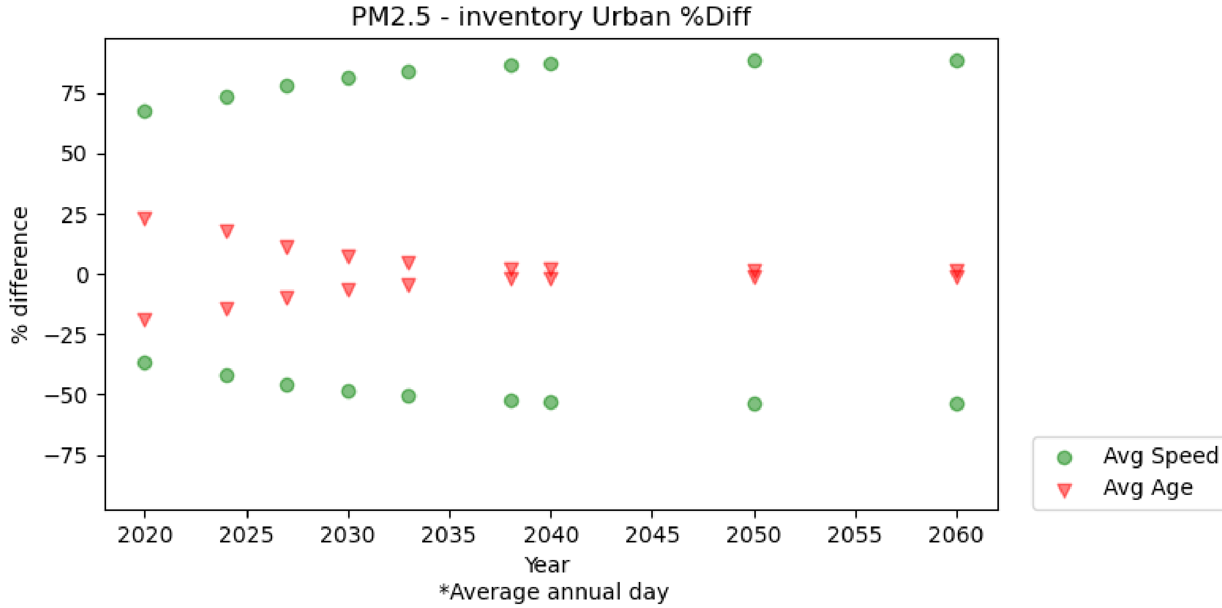


Figure 80. PM$_{2.5}$ Urban Inventory



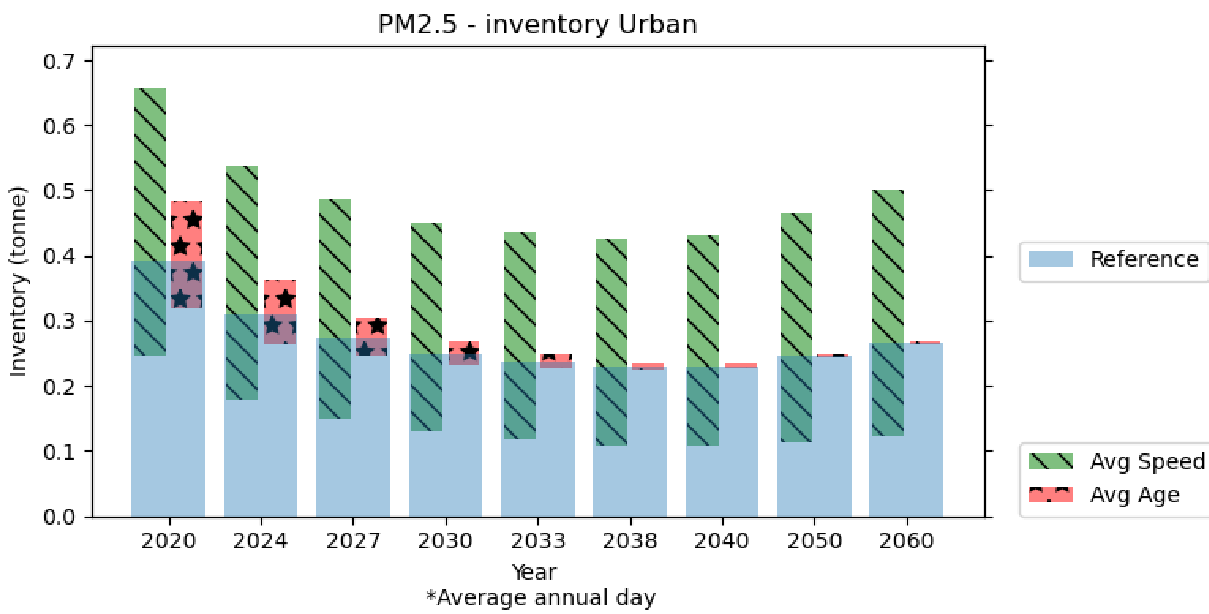


Figure 81. $PM_{2.5}$ Rural Inventory

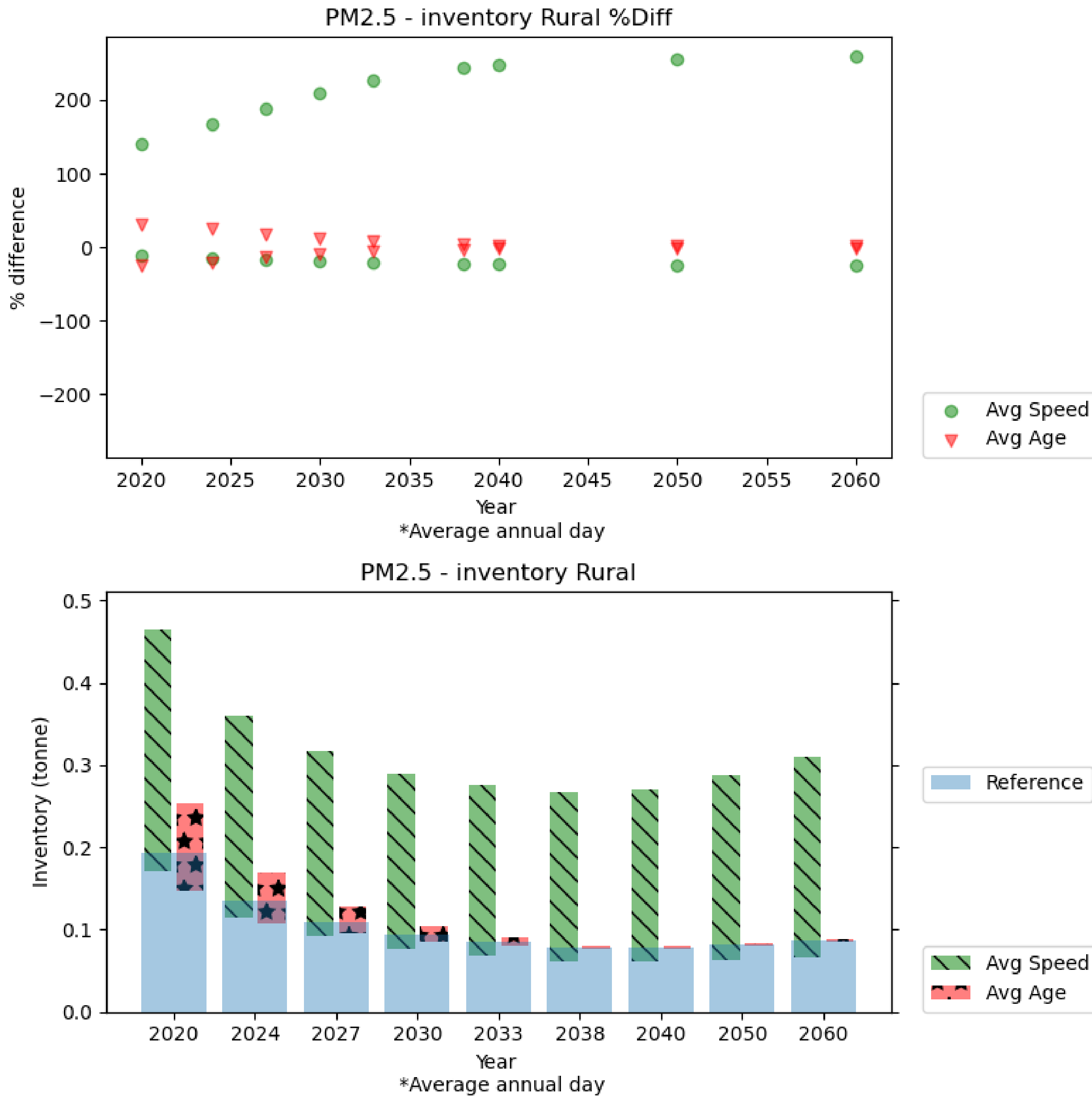


Figure 82. PM_{10} Urban Inventory

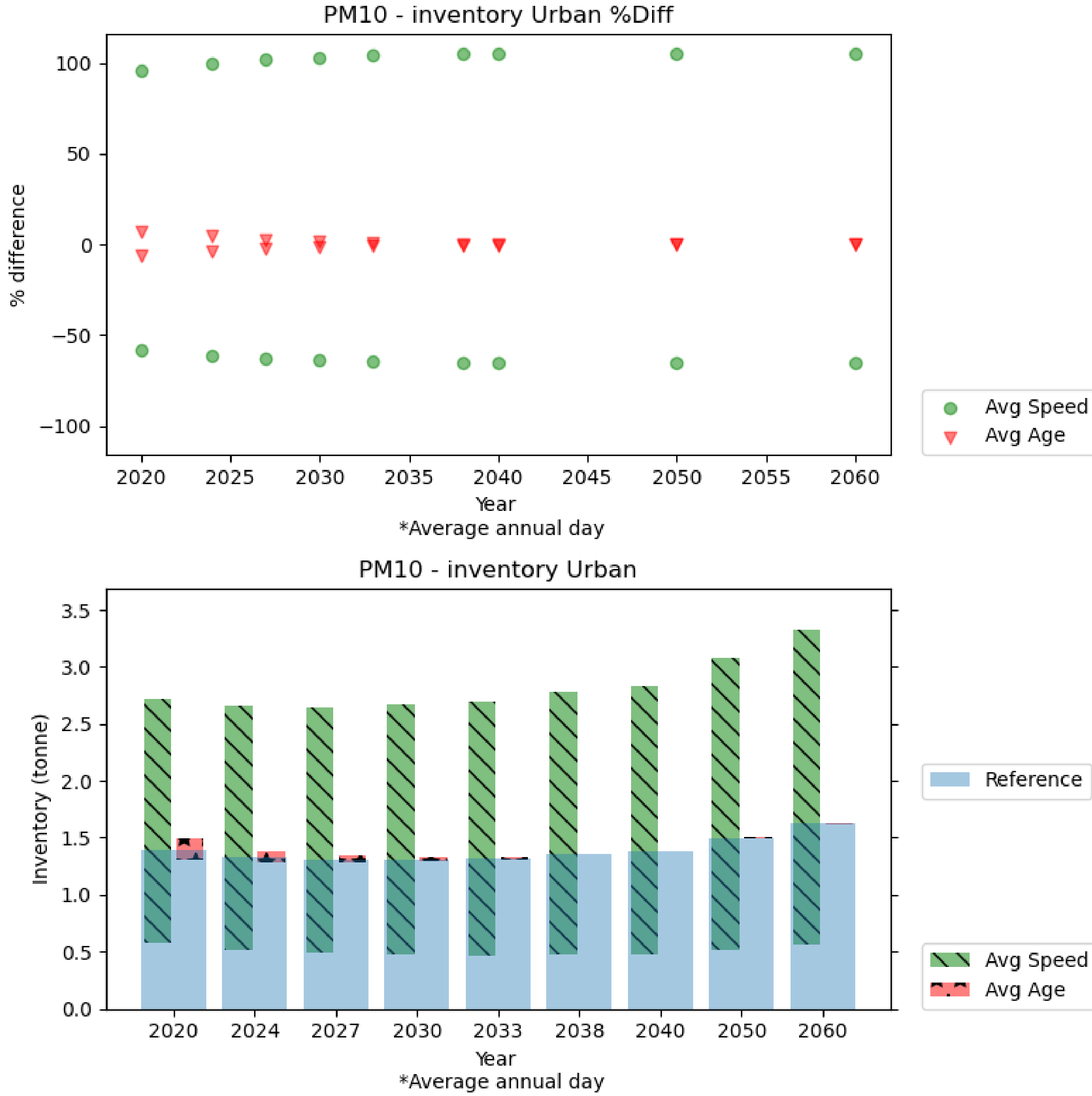


Figure 83. PM_{10} Rural Inventory

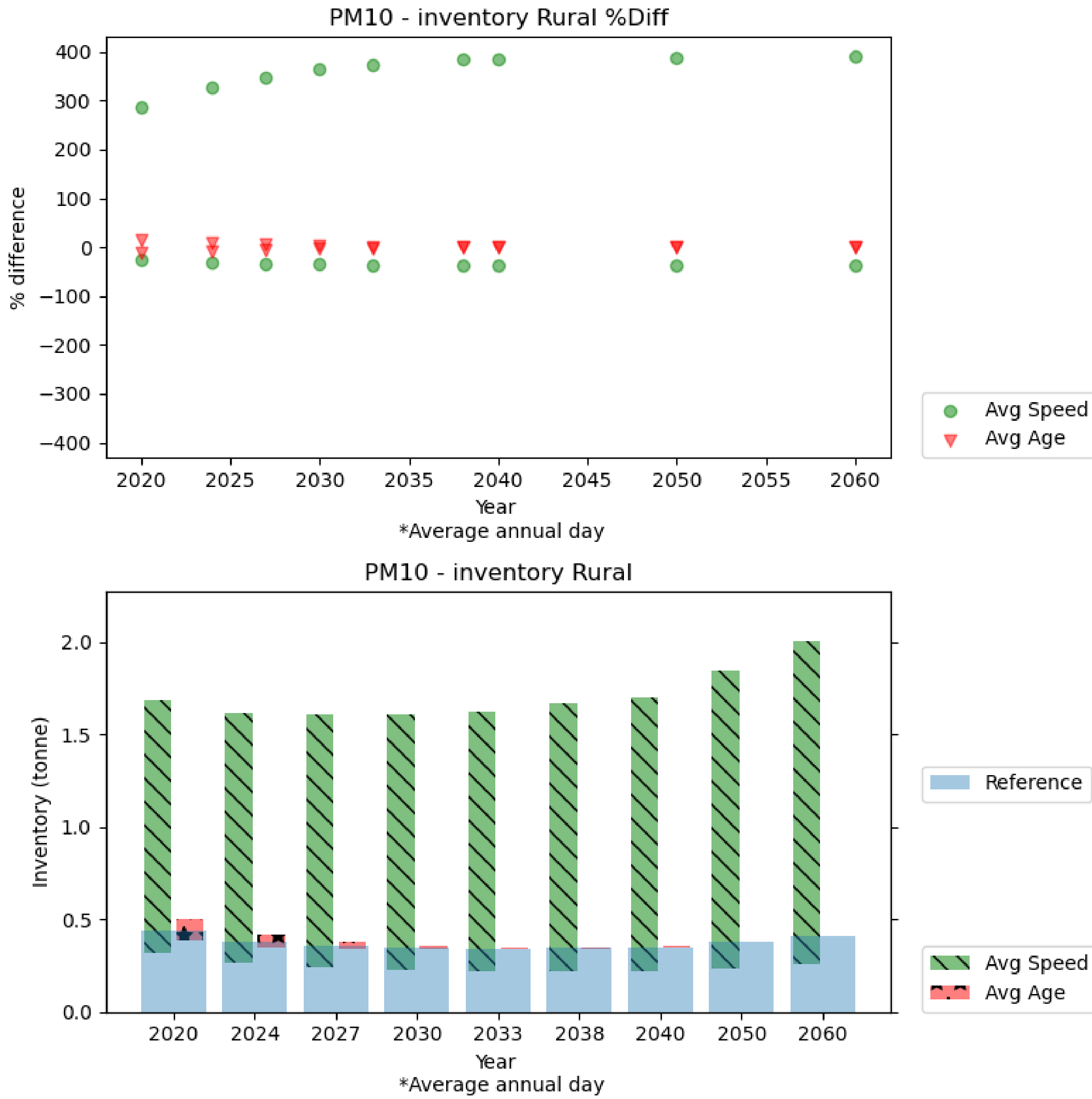
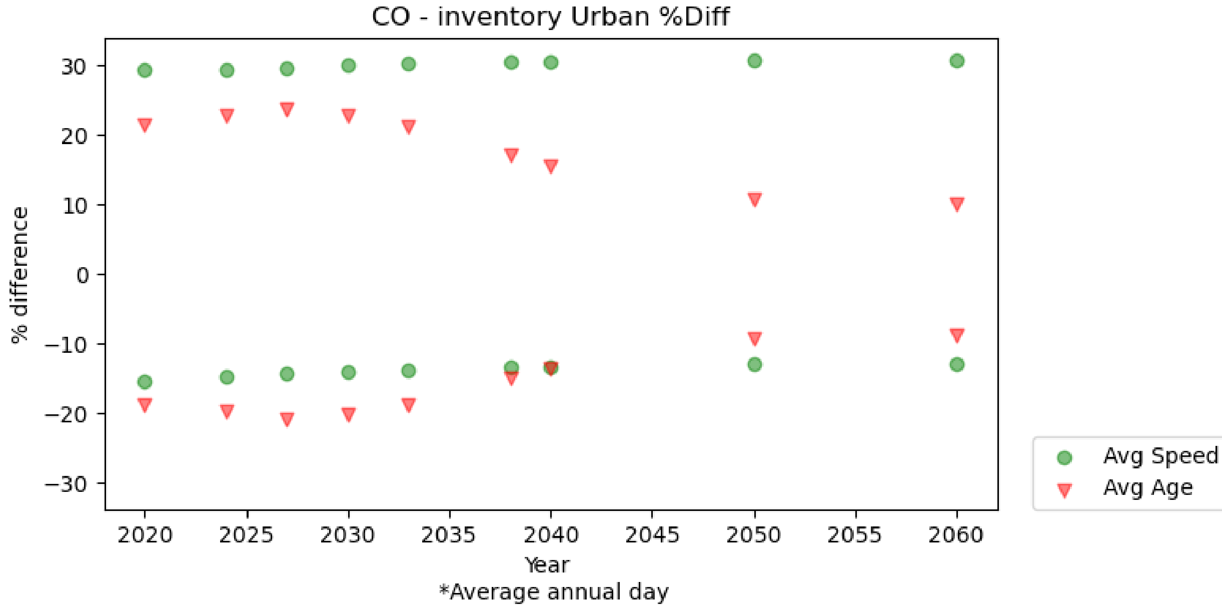


Figure 84. CO Urban Inventory



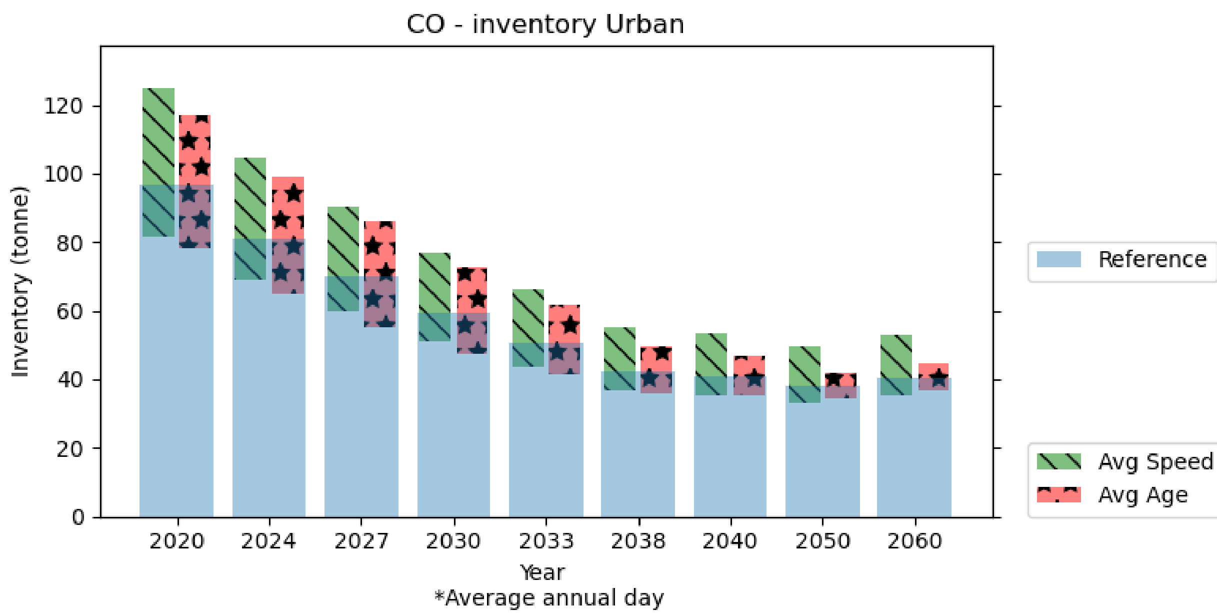
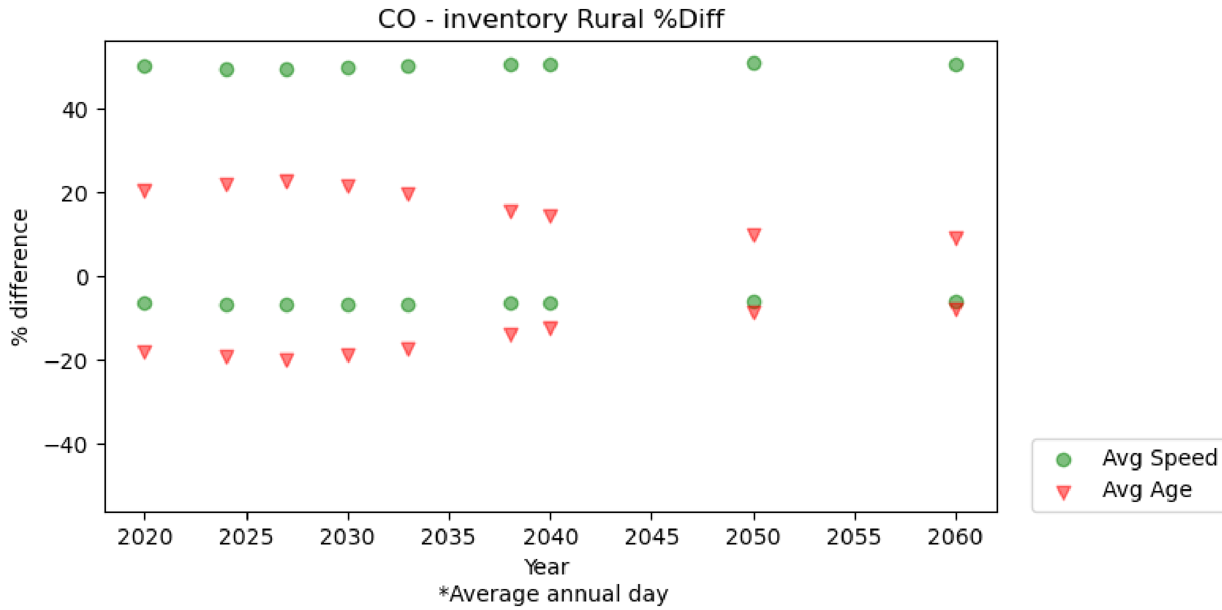


Figure 85. CO Rural Inventory



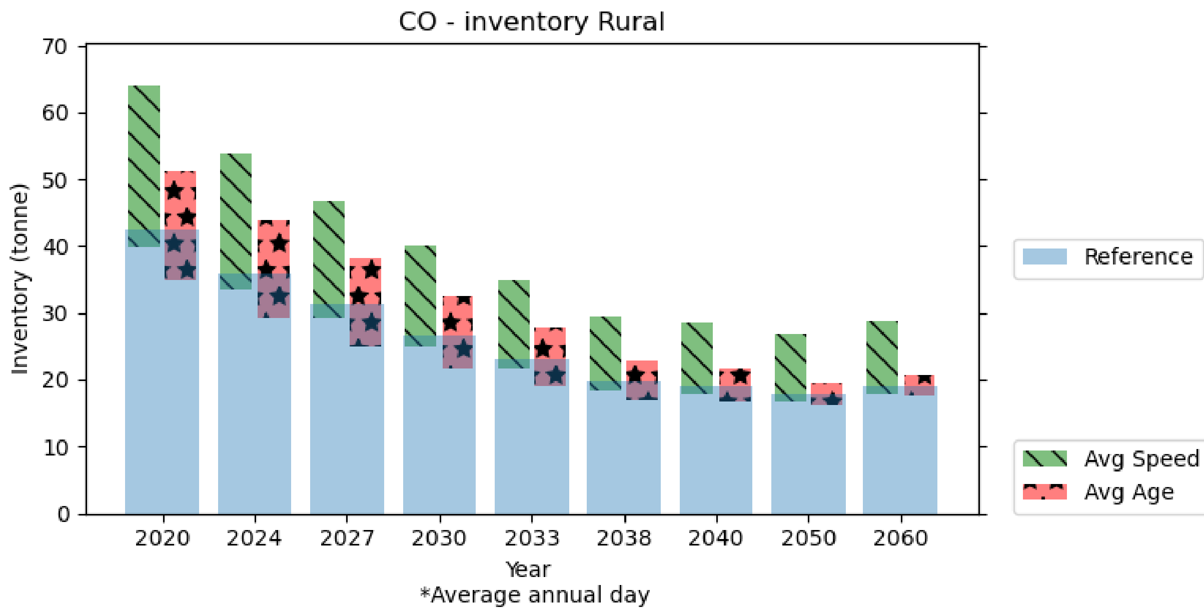
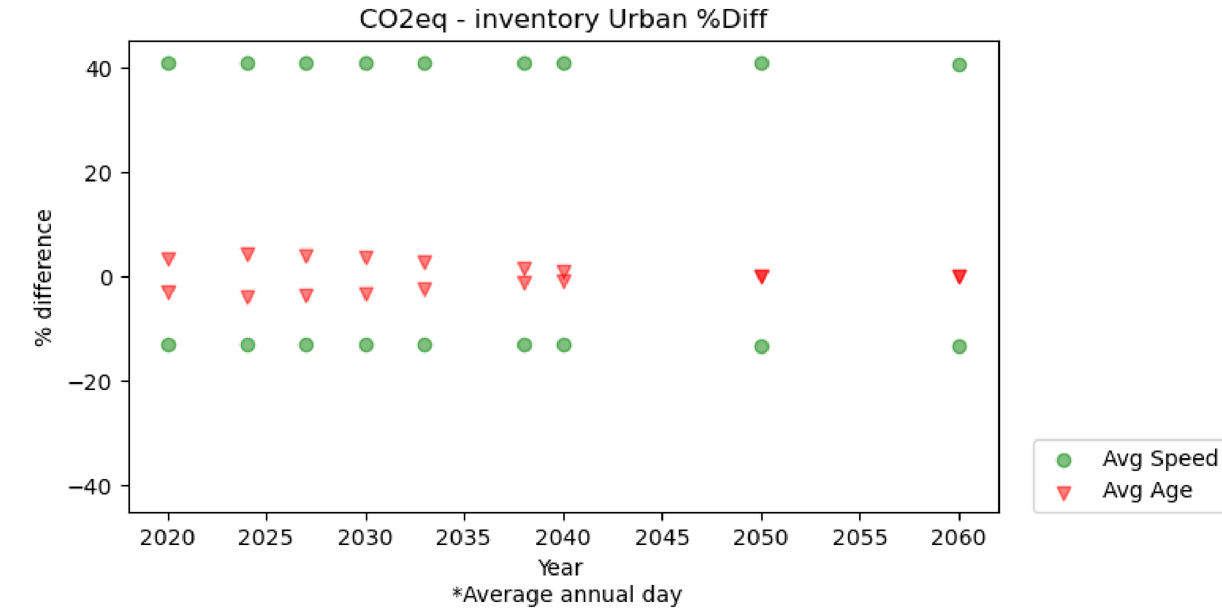


Figure 86. CO_2eq Urban Inventory



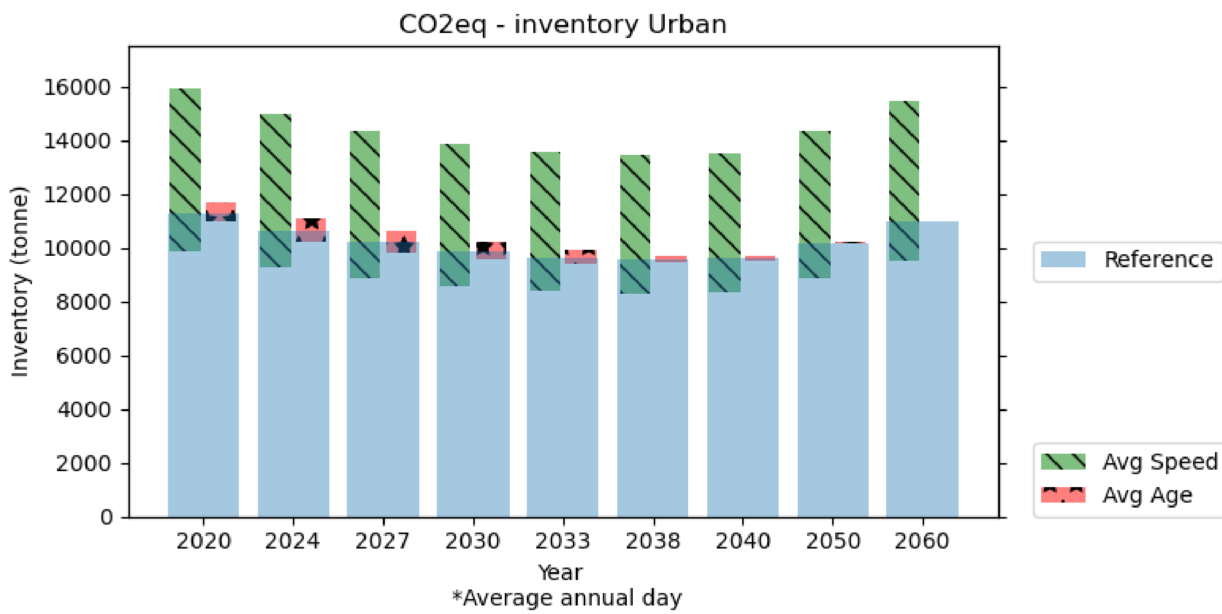


Figure 87. CO_2eq Rural Inventory