# WHITE PAPER ON AIR QUALITY AVIATION IMPACTS ON AIR QUALITY: STATE OF THE SCIENCE

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* This White Paper represents the summary of the scientific literature review undertaken by researchers and internationally-recognized experts. It does not represent a consensus view of ICAO.

## Summary

Aircraft produce emissions that react in the atmosphere to form pollutants that impact air quality. These emissions have long been regulated through standards for aircraft engines for oxides of nitrogen (NOx), carbon monoxide (CO), unburned hydrocarbons (UHC), and smoke, via a Smoke Number (SN). New standards are being developed for non-volatile particulate matter (nvPM). Much is understood about how these and other emissions affect air quality in airports and in the regions around them. Ongoing research efforts are extending that understanding through better measurements and modelling. Work on PM is directed at developing the new nvPM standard, and increasing the available data on aircraft engine PM emissions. Alternative fuels have the potential to reduce PM emissions significantly. Emissions inventories are developed to calculate the contributions of all emissions to the ambient burden of pollutant concentrations that, in turn, are used to estimate the impacts on air quality and human health. Aircraft emissions at cruise altitude can also propagate back to affect local and regional air quality, and estimates of this contribution and the associated uncertainties have been calculated.

The impact of aircraft emissions on air quality was the concern that gave rise to the first State aircraft emissions regulations that were imposed in the 1960s and 1970s. ICAO adopted stringent standards in 1981 that were applied to all in-production engines in 1986. Air quality issues related to aircraft emissions were reviewed in the 2007 ICAO Environmental Report (ICAO, 2007), covering technology and standards, operational measures, market-based measures, and airport charges guidance. Growing interest in the effects of Particulate Matter (PM) on human health and climate has brought a new focus on measuring aircraft PM emissions. Background and current issues of PM were summarized in the 2013 ICAO Environmental Report in the section titled "Development of a Particulate Matter Standard for Aircraft Gas Turbine Engines" (ICAO, 2013).

Aircraft turbofans (> 26.7 kN thrust) are currently regulated for their emissions, which include oxides of nitrogen (NOx), unburned hydrocarbons (HC), carbon monoxide (CO), and smoke. The smoke regulation also applies to engines with output ratings < 26.7 kN. Smoke emissions are mainly carbonaceous particles emitted as a product of incomplete combustion, and these particles are now the subject of a proposed new standard that will regulate the number and mass of non-volatile particles (nvPM). Airport emissions are also affected by emissions from other sources such as Auxiliary Power Units (APUs), ground service vehicles, and include other sources such as ground transportation and power plants. These various emissions interact with each other, and thus each contribution to the total regional inventory of pollutants must be quantified and evaluated as accurately as possible.

Aircraft engines are successfully meeting increasingly stringent emission requirements. However, more stringent and new requirements are being considered as the understanding of emission impacts on the environment and human health is improved. The need for a new nvPM standard that goes beyond the existing Smoke Number measurement is a prime example of this evolution. Similarly, the ever-increasingly stringent standard for NOx is complemented by a growing concern over the impact of the $NO_2$ component of NOx (NOx consisting of NO plus $NO_2$).

This report focuses on the impacts on air quality, as opposed to climate impacts, due to emissions from aircraft combustion engines, including both propulsion engines and APUs. While it is understood that aviation operations include other sources of emissions, they will not be further discussed or analyzed here. As the health and welfare impacts of particulate matter and ozone are well understood and the underlying science has not changed since the last ISG review of aviation's impact on surface air quality, this review focuses on advances in the scientific community's understanding of the emissions that come from the aircraft tailpipe and how these emissions react and disperse in the atmosphere to form ground level PM and ozone ($O_3$). There is a continuing need to better understand the relative impacts of particle number versus particle mass, fine PM versus ultrafine PM, as well as the relative toxicity of the various ambient and aviation PM components. However, there are no new results on these issues to report at this time.

## Measuring and Modelling Emissions

**Figure 1** provides a representation of aircraft emissions and how they ultimately contribute to ambient pollutant concentrations that impact public health and welfare. While aircraft emissions can be directly measured at the source and ambient pollutant concentrations can be measured at any location, modelling is required to attribute the contribution of aircraft to ambient pollutant concentrations.

Ambient measurements in the vicinity of airports typically show little to no contribution from airport emissions (Zürich Airport, 2013). However, recent studies have shown elevated PM number levels near airports (Hudda et al., 2014; Keuken, et al. 2015). Measurement protocols and guidance are established for criteria pollutants. However, the ambient measurement of ultrafine particle number concentrations is not yet standardized.

## Non-Volatile Particulate Matter (nvPM) Emission Characterization and Quantification

New sampling techniques have been developed and are being finalized for quantifying nvPM mass and number emitted from gas turbine engines (SAE, 2013). Various measurement campaigns have been performed to develop and assess the operability of the sampling methodology (Crayford et al., 2012, Lobo et al., 2015). An instrument manufacturer has developed a commercially available sampling system (AVL, 2015) and OEMs have started to include nvPM measurements in engine certifications. These are challenging measurements since particles are difficult to quantify with high accuracy, and this is compounded by the high temperature, high velocity environment present in the aircraft exhaust.

A particularly difficult challenge in the nvPM measurement arises due to the fact that there is not a straightforward way to calibrate PM instruments and there is not a clear chemical definition of the material that composes the nvPM. For gases, a precise mixture can be prepared that simulates gaseous emissions in the exhaust, which can then be used to calibrate measurements of species like NOx, HC, and CO. Conversely, particle standards are neither easily prepared nor referenced. This problem of the lack of a robust calibration standard, combined with inherent uncertainties in the PM measurements themselves, will need to be considered in how levels and margins are established in setting the new nvPM standard. Furthermore, for the use of nvPM data in emission inventories, an accurate and robust line loss correction methodology is essential. The line loss correction methodology is in the process of being established with open questions regarding the magnitude of its uncertainty and its robustness.

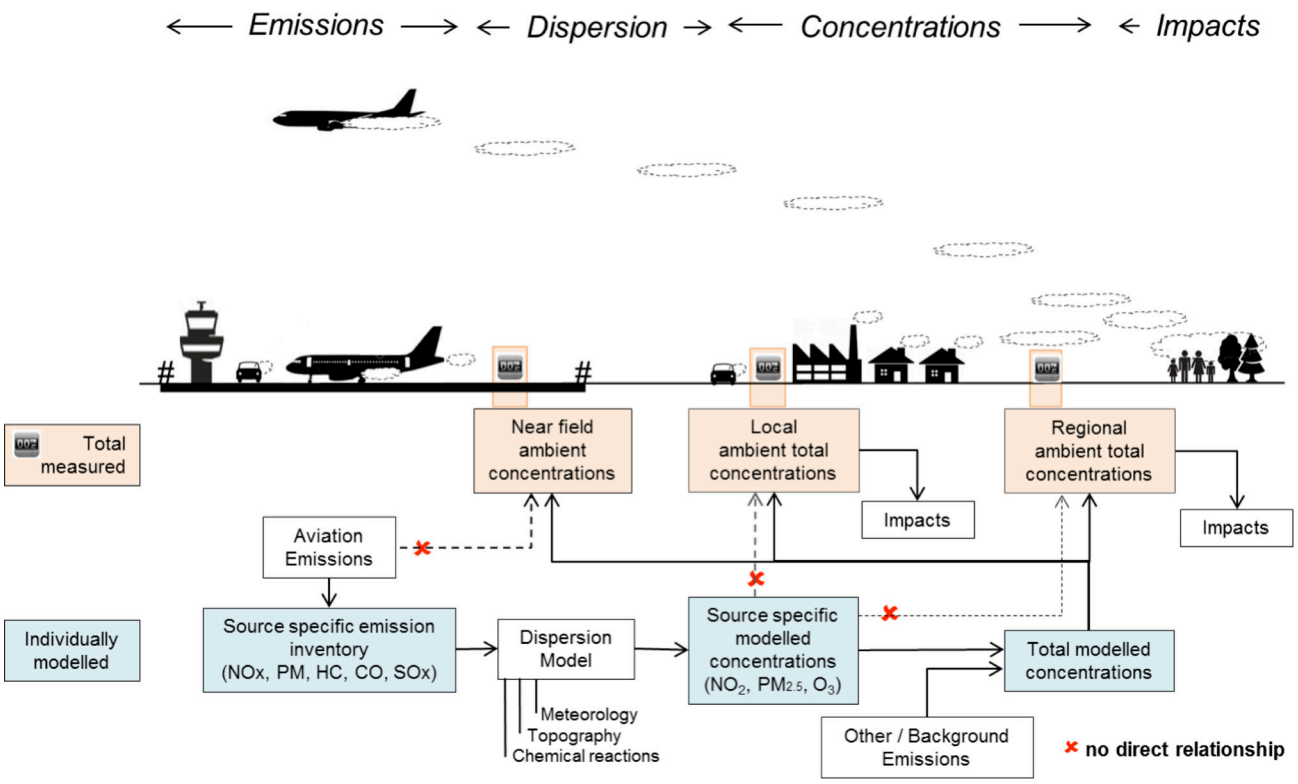


**Figure 1.** Schematic presentation of emissions, dispension, concentrations and impacts with their interaction at airport level

Exhaust sampling campaigns, which were mainly focused on the nvPM sampling methodology development, also improved the knowledge on particle size distributions, particle effective density, morphology and internal structure of aircraft PM (Durdina, 2014; Johnson, 2015; Liati, 2014; Corbin, 2014). These properties are critical for the understanding of the fate and potential health impacts of these particles. These studies add to the body of data on aircraft engine PM emissions and the volatile contributions to PM from sulfate and organics (Timko et al., 2010, Yu et al, 2010, Timko et al., 2013).

In addition to the main propulsion engines, aircraft can also contribute particles due to PM arising from tyre and brake wear during landing and from operations. Recent work (ACRP, 2013) has quantified these emissions and, while important for inclusion in a comprehensive inventory, their contributions compared to main engine emissions range from negligible for tyres and brakes to modest for APU under routine operations.

## PM Emissions from Alternative Fuel Combustion

The need for developing sustainable fuels for aviation has sparked an interest in bio-derived fuels. Despite a range of existing commercial challenges, there are a number of concrete projects to start regular supply of sustainable alternative fuel to airlines at some airports, such as LAX, AMS, OSL and BNE, potentially already in 2015, at a blend ratio in the 1% range.

Such fuels need to meet the requirements of aviation operations, yet may still allow for a range of specific fuel compositions, which lead to variations in emissions compared to conventional jet fuel. Their effects on air quality should be considered at airports that, in the future, will provide alternative fuel blends. In evaluating Alternative Jet Fuel (AJF) candidates, the resulting changes in PM emissions have also been measured. Specifically, the lower fuel aromatic and fuel sulphur levels with the majority of AJFs under consideration have the potential to reduce PM emissions from aircraft and APUs.

Synthetic Paraffinic Kerosene (SPK) fuels are better understood than other AJFs that are being considered by industry; they have reduced PM emissions due to their lower aromatic composition and typically lower sulphur content. **Figure 2** provides a summary of the wide range of PM mass and number emissions measurements that have been taken in recent years (note the figures refer to PM as black carbon). The measurements consistently show that the reduced aromatic content of SPK fuels and blends of conventional jet fuel and SPK fuels results in reduced PM. Similar reductions have also been observed for APUs (Lobo et al. 2015) and models have been developed for accounting for fuel effects in PM mass and number emissions (Speth et al, 2014; Moore et al., 2015; Brem et al., 2015).

It is important to note that AJFs offer a complementary route to reducing PM emissions to that offered by improved combustor technologies that have been lowering PM emissions while using standard jet fuels over the past decades.

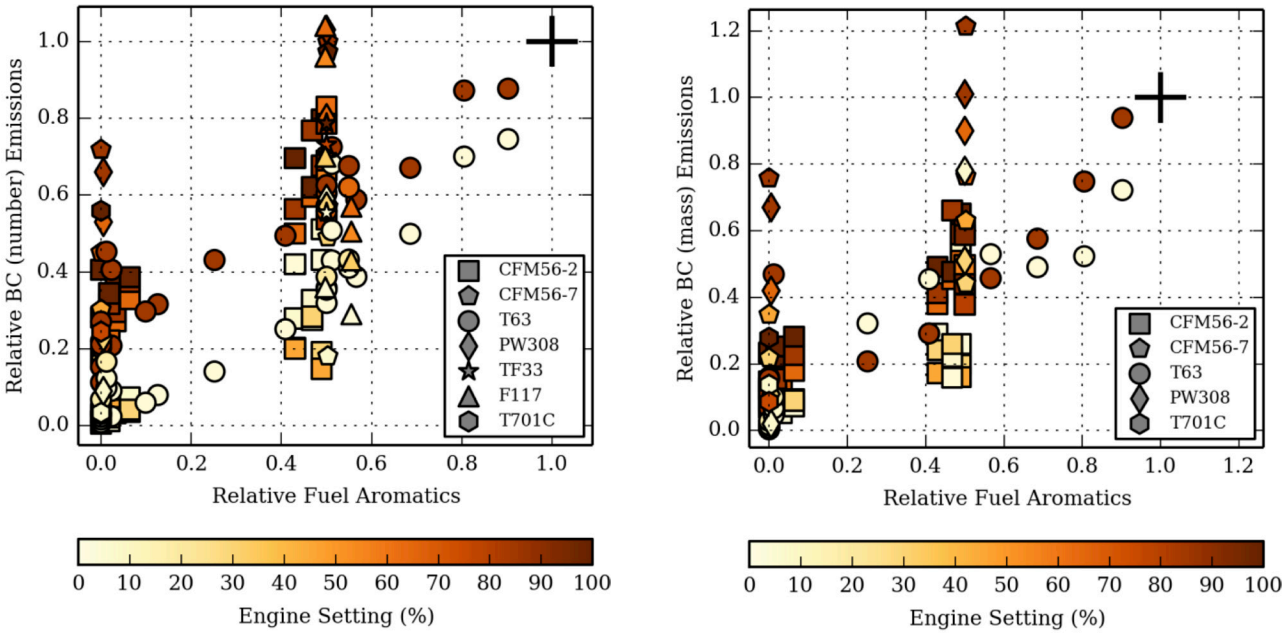


**Figure 2.** Measured normalized black carbon (BC) number and mass emissions as a function of normalized aromatic content and engine setting (Speth et al., 2014).

## Emissions Inventories

Data on emissions provide the primary source values for individual particulate or gaseous substances emitted by combustion, industrial or mechanical processes. The individual emissions are initially determined by measurements under a controlled environment and set activity. For aircraft engines, these emissions are usually measured at the engine exit plane.

Emission inventories from aviation (or similarly from other sources) are produced by modelling the total amount of mass per time period. These are modelled using measured emissions data in combination with known operational data for the use of aircraft in the airport for which the inventory is being developed (emissions = activities x emission factors). Often total airport inventories are developed for a given time period, such as a total annual inventory. If further analysis is required, temporal and spatial resolution is needed (Ref: ICAO, Doc 9889, Airport Air Quality Manual).

In developing detailed airport inventories, the necessary data to describe aircraft operations are not all available with sufficient accuracy or granularity. Typical times-in-mode (especially duration of taxi-in and out and turnaround) strongly depend on the layout of each airport and on operational characteristics such as preferred gate occupation, frequency of departure queues and habits of APU use. Power setting profiles for take-off/climb and approach depend on prescribed flight procedures (mainly for noise abatement reasons) and also vary between airlines or aircraft types. At many airports they are not systematically recorded even as average values. All of these effects result in noticeable uncertainties in modelling aircraft emissions.

Emissions measurements help improve the creation of emissions inventories. For example, estimates of non-volatile PM (nvPM) from aircraft using Smoke Number (SN) are uncertain. Recent

| Source | Activity | Emission factor | Calculation |
|---|---|---|---|
| Aircraft engine | Stop & go behaviour, Idle vs taxi, flex take-off | ICAO Engine Emissions Data Bank, but not yet PM | BFFM2, but FOA for PM |
| Auxiliary Power Unit (APU) | Environmental Control System Duration | Rudimentary in Doc 9889 | Simple product |
| Aircraft frame | Brakes, tires | Assumptions | Simple product |
| Ground Support Equipment (GSE) | Machinery good, else poor | EU Non Road Mobile Machinery (EUNRMM) | Simple product |
| Stationary Sources | Usually well known | EMEP-EEA, manufacturer | Simple product |
| Landside vehicles | Fair, many assumptions | HBEFA, Coppert, etc. | Simple product |

**Table 1.** Level of understanding in airport emission inventory: green (good); yellow (fair); red (poor) (Updated from Forum-AE, 2014)

studies have shown that nvPM emissions estimated using SN value as in First Order Approximation 3 (FOA3) can underestimate actual nvPM quantities by a factor of ~3 (Stettler et al, 2013), and these were corroborated in a recent study at the Los Angeles International - a large U.S. airport (Penn et al, 2015). The use of certified data for evaluating nvPM engine emissions on operational phases will improve these estimates.

Some of the gaps for the production of airport emission inventories are displayed in **Table 1**.

## Model Emissions Dispersion and Concentrations

Substances once released into the atmosphere undergo a more or less rapid transformation based on ambient conditions and chemical properties. For instance, aircraft produces mainly NO or $NO_2$ as a function of the power used on the different operational phases; then, the transition between both forms or toward other nitrogen compounds is a function of ambient chemical compounds that react with them, as well as temperature and available sunlight. Gaseous aircraft emissions can influence the local levels of ozone, and some can also eventually contribute to ambient PM formation. Both the emitted particles and the particle precursor gases contribute to ambient nucleation mode particles, $PM^{2.5}$, and $PM^{10}$. In addition to chemical transformation, atmospheric processing likewise includes dispersion over time and space, leading to spatially and temporally varying concentrations of the emitted pollutants and their resulting chemical and particle products.

Assessing the concentrations in a regional airshed can be done by either measuring them directly or estimating their concentrations by modelling them based on emissions inventories. The challenge lies in that measuring the ambient concentrations will always include all “contributing” emissions – whether aviation related or not. Modelling the concentrations provides the option to only assess aviation related emissions (source discriminated), but additional effort is needed to numerically model total ambient concentrations that includes all sources and non-aviation background concentrations. In consequence, a careful interpretation and source apportionment of ambient measurements is necessary.

## Modelling the Contribution of Aircraft Emissions on Air Quality

On a global scale, emissions from commercial aviation activity (due to LTO and cruise-mode) contribute to less than 3% of total anthropogenic emissions for NOx, and even less (< 1%) for all other primary pollutants such as CO, NMVOC, PM10 and SO2. However, on a local scale near large airports, such as Atlanta Hartsfield, aircraft emissions of NOx during LTO can be as high as 5%. Transportation related sources contribute up to 46% for NOx, and between 4.6 – 32.7% for other pollutants. As a percent of all transportation-related sources, commercial aviation contributes about 6% for NOx, and 0.3 – 2.3% for the other pollutants. (Source: EC 2011)

The topography around each airport, as well as time-varying wind direction and speed, can have a significant effect on the dispersion of emissions. Non-aviation sources, especially the pattern of roads accessing and surrounding airports, but also stationary industries, have a considerable impact on air quality, which is often larger than aircraft operations.

For the simplified characterization of air quality impacts and source attribution, emission inventories from various sources are often used as a surrogate. In the case of aircraft, the landing and take-off Cycle (LTO) is such an assumption. However, only emissions up to approximately 3,000 ft above ground level directly contribute to the surface concentrations near the airport; emissions above are dispersed more widely (Umweltbundesamt, 1992). To this end, emission inventories from aviation would have to be adjusted for that and the difference e.g. for NOx can be 30-40% (EUROCONTROL, 2006).

Current tools and methods allow for more advanced modelling, including not only airport related sources, but often also emissions from other contributors. Such overall modelling will enable the practitioner to actually compare modelled and measured pollutant concentrations at selected receptor points (i.e. measurement stations) and determine the contribution from aviation. However, this requires substantial additional effort. Studies show that airport related contributions quickly drop with increasing distance from the source, as well in absolute values as in relative share of contribution (Zurich Airport, 2013).

Aircraft emissions affect ambient air quality, specifically the concentrations of $O_3$, $NO_2$, $PM_{2.5}$ and Hazardous Air Pollutants (HAPs) or air toxics. The chemical reactions of aircraft-emitted species with other background chemicals often occur at downwind distances of up to 200-300 km away from the airport (Arunachalam et al, 2011; Rissman et al, 2013). However, the contribution of aircraft-related air quality impacts for $PM_{2.5}$ to the total ambient air are often in the range of 1-5%, (the higher end of this range applicable for large airports such as Atlanta Hartsfield when modelled at fine resolution) and given the magnitudes of the health-based air quality standards, do not lead to violations of air quality standards on their own. Furthermore, aircraft emissions of NOx and SOx react with ammonia emitted from non-aviation sources to form inorganic $PM_{2.5}$ such as ammonium nitrate and ammonium sulfate. In future years, aircraft-attributable $PM_{2.5}$ levels are likely to be a stronger function of ambient $NH_3$, and could lead to a disproportionate amount of inorganic $PM_{2.5}$ formed greater than simply the growth in the aviation-emitted primary precursors (Woody et al, 2011). However, moving to a desulfurized jet fuel from the current levels will likely mitigate some of this projected contribution in the future.

**Figure 3** shows the contribution of each of 66 U.S. airports to total ambient PM2.5 in absolute and relative terms, and as a function of annual LTO operations (Boone et al, 2015). Given the complexity associated with the total PM2.5 formed from primary and secondary components, one can see that the airport with the highest LTO operations do not lead to the highest amount of PM2.5.

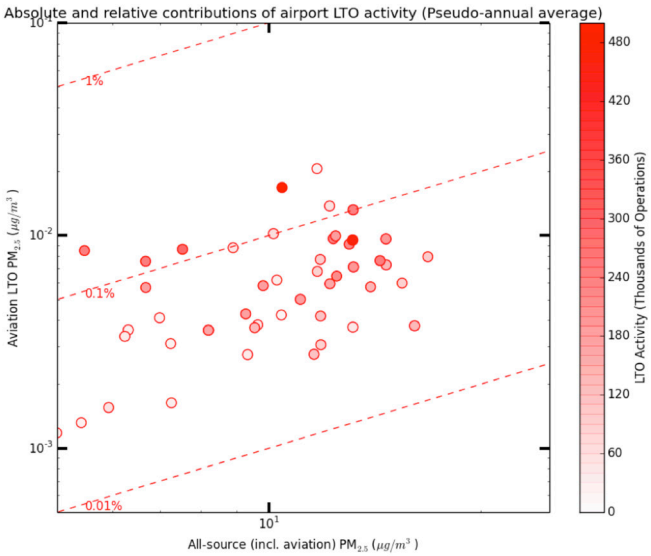


**Figure 3. Individual airport-attributable PM2.5 contributions compared to all-source contributions as a function of airport operations (each dot represents one of the top 66 U.S. airports, and the dotted line shows the % of airport-attributable PM2.5 compared to total PM2.5 from all sources)**

New classes of semi-volatile and intermediate volatility organic compounds (S/IVOC) precursors that lead to the formation Non-Traditional Secondary Organic Aerosols (NTSOA) have been identified by recent smog-chamber studies (Miracolo et al, 2012). These studies showed that traditional SOA models could under predict traditional SOA formation by up to ~60% at engine loads of 4% and ~40% at 85%. However, when incorporated in comprehensive grid-based models, these precursors led to relatively modest increases in SOA formation, due to the relatively low levels of ambient organic aerosols, but still contributed to about 24% of the total aircraft-attributable PM2.5 (Woody et al, 2014).

The main uncertainties in ambient air quality studies lie in understanding the effects of the granularity of models, and the micro-meteorological and chemical reaction effects. The granularity of models includes the information on emissions (emission factors for the relevant sources, actual operations of those sources, e.g. the APU) and the assessment of temporal and spatial resolution. Microscale meteorological and chemical reaction effects include issues like plume-rise and turbulence of exhaust plumes and heterogeneous chemical reactions that are currently not well modelled.

## Cruise Emissions Impacts on Air Quality

The FAA has been funding a multi-institute study[3] to compare the impacts of emissions from commercial aircraft activities worldwide on surface ozone (O3) and fine particulate matter (PM2.5; size less than 2.5 micrometers) global chemistry-climate models. The models include climate-response models (CRMs) with interactive meteorology, chemical-transport models (CTMs) with prescribed meteorology, and models that integrate aspects f both. The models all used the same 2006 inventory of global ommercial aviation emissions.

ll of the models in the study find that aircraft increase near-urface ozone (0.4 to 1.9% globally) and the perturbations in the lorthern Hemisphere are highest in the winter, when ambient zone levels are lower and potentially of not as much concern o human health compared to the higher ozone in the summer nonths. Changes in surface-level PM2.5 in the CTMs (0.14 o 0.4%) and CRMs (-1.9 to 1.2%) appear to depend on the ackground aerosol fields and these vary considerably among ne models. The inclusion of feedbacks in meteorology also as a strong impact on the results. The CTMs tend to show an ncrease in surface PM2.5 primarily over high-traffic regions in ne North American mid-latitudes. The CRMs, on the other hand, emonstrate the effects of changing meteorological fields and otential feedbacks on aviation emission impacts, and exhibit large perturbations over regions where natural emissions (e.g., soil dust and sea spray) are abundant.

1. At the time this draft white paper was assembled, the report was in review with the FAA. The research team consists of Stanford University, Massachusetts Institute of Technology, National Center for Atmospheric Research, NASA Goddard Space Flight Center, Yale University, and the University of Illinois at Urbana-Champaign.

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