WHITE PAPER

Brake Emissions at the Base of Teton Pass, Wyoming

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This document contains blank pages to accommodate two-sided printing.

Cover photo: *Air quality measurement site at the base of Teton Pass in Wilson, WY during July 10-24, 2018. This site was part of the 2018 study "Assessing Impacts to Air Quality from Vehicle Emissions in Teton County, WY" (Wright, 2019).*

Table of Contents

1. Introduction

This White Paper is focused on topics related to brake emissions at the base of Teton Pass in the town of Wilson, Wyoming. There is concern in this area surrounding possible adverse public health effects due to brake emissions associated with eastbound traffic descending Teton Pass. Vehicle traffic on WYO Highway 22 over Teton Pass and into the Town of Jackson and surrounding areas can range from 13,000 to greater than 22,000 vehicles per day (Jackson/Teton County Comprehensive Plan, 2018 Annual Indicator Report). This White Paper is intended as an addendum to the Final Report “Assessing Impacts to Air Quality from Vehicle Emissions in Teton County, WY” (Wright, 2019).

The base of Teton Pass is characterized by vehicle traffic (car / truck / heavy truck) on two lanes (Hwy 22) through Wilson, WY. This area tends to have heavy “rush-hour” periods associated with eastbound (morning) and westbound (evening) commuter traffic (Figure 1.1). The speed limit is 25 mph, increasing to 45 mph on either side of the town of Wilson.

This White Paper covers six specific “Topics of Interest”, as originally outlined by the Teton Conservation District (TCD). Specific questions from the TCD are included in bold for each Topic of Interest.

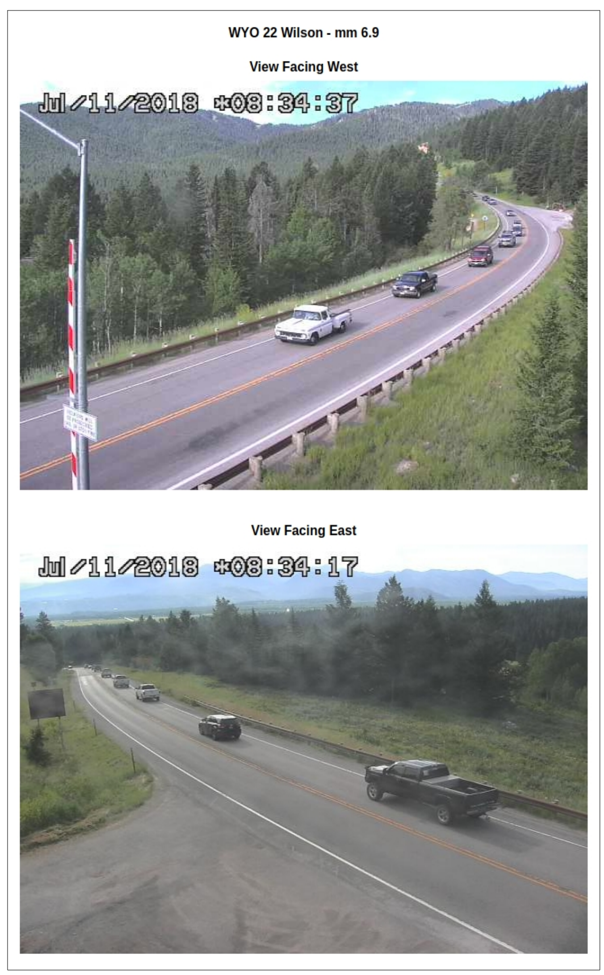

Figure 1.1: *Time-lapse camera image showing traffic conditions in downtown Wilson, WY on July 23, 2018 (above) and WYDOT webcam images for Highway 22 on July 11, 2018 (right). Commuter traffic between Teton County, WY and Teton County, ID can create congested traffic conditions over Teton Pass and in the town of Wilson, particularly in summer months with increases in tourism-related traffic.*

2. Topics of Interest

2.1 Constituents for brake emissions monitoring

- ***What constituent(s) need to be monitored to measure brake emission levels at the base of Teton Pass?***

Brake emissions exist as particulate matter, generated from both thermal/chemical and mechanical processes. The emitted particles are a result of brake pad wear and rotor wear (Figure 2.1), with the chemical composition of the particles reflecting the composition of these components. Particle size can range from nanoparticles less than 100 nm up to coarse particles in the PM_{10} size class.

In general, finer particles are generated from thermal/chemical processes, and coarse particles are generated from mechanical processes (Fig. 2.2). The mass size distribution for brake wear particles tends to peak in the range of 2-4 µm, with tails of the distribution extending below 2 µm and up to 10 µm. The number distribution tends to be bimodal in the fine particle mode (< 2 µm) (Grigoratos and Martini, 2015). Therefore, measurement of both $PM_{2.5}$ and PM_{10} are necessary to monitor brake emissions. The EPA-regulated size classes for particulate matter are as follows:

- **$PM_{2.5}$:** Particles with a diameter smaller than 2.5 micrometers (µm, or microns). Also called fine particles.
- **PM_{10} :** Particles with a diameter smaller than 10 µm. Also called inhalable coarse particles.
- Particles larger than 10 µm (e.g., sand and large dust) are not regulated by the EPA.

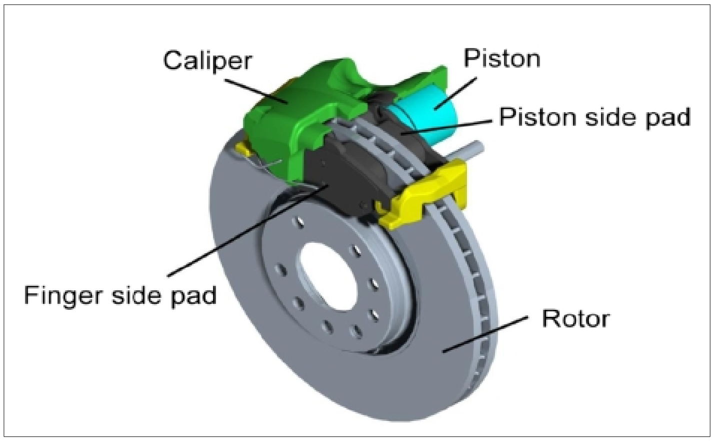

Figure 2.1. *Graphic representation of a disc brake system. Source: [Wahlström 2009]*

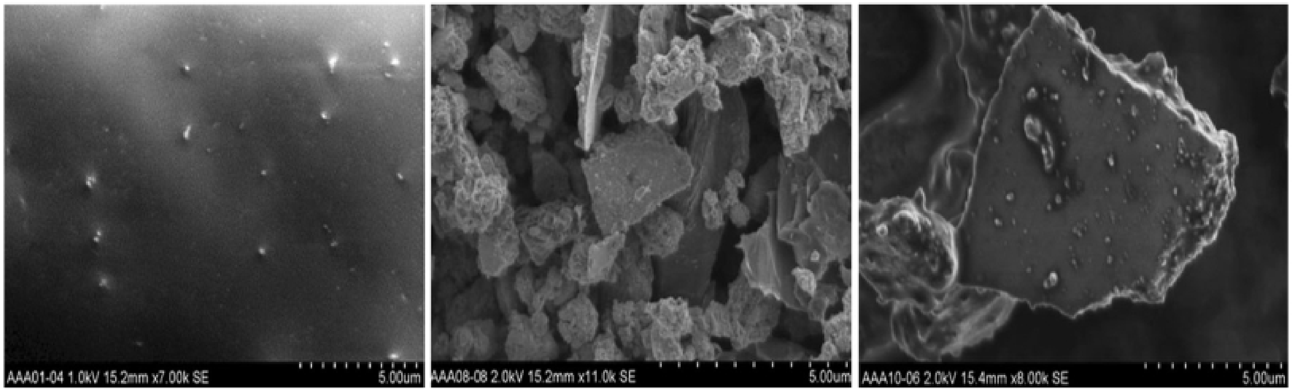

Figure 2.2. *SEM images of brake wear particles (left <56 nm, middle $PM_{2.5}$, right PM_{10}). Note that a human hair is approximately 60 µm in diameter. Source: [Kukutschová et al. 2011]*

Exhaust and non-exhaust sources are estimated to contribute approximately equally to traffic-related PM_{10} emissions. Brakes are a major source of non-exhaust PM_{10} emissions, and can contribute up to 21% of traffic-related PM_{10} emissions (Figure 2.3) (Grigoratos and Martini, 2015). Exhaust sources are dominated by fine particles, whereas non-exhaust sources (including brakes) can span both fine and coarse classes. Due to continuous reduction of vehicle exhaust emissions, it is expected that the relative contribution of non-exhaust sources will increase over coming years.

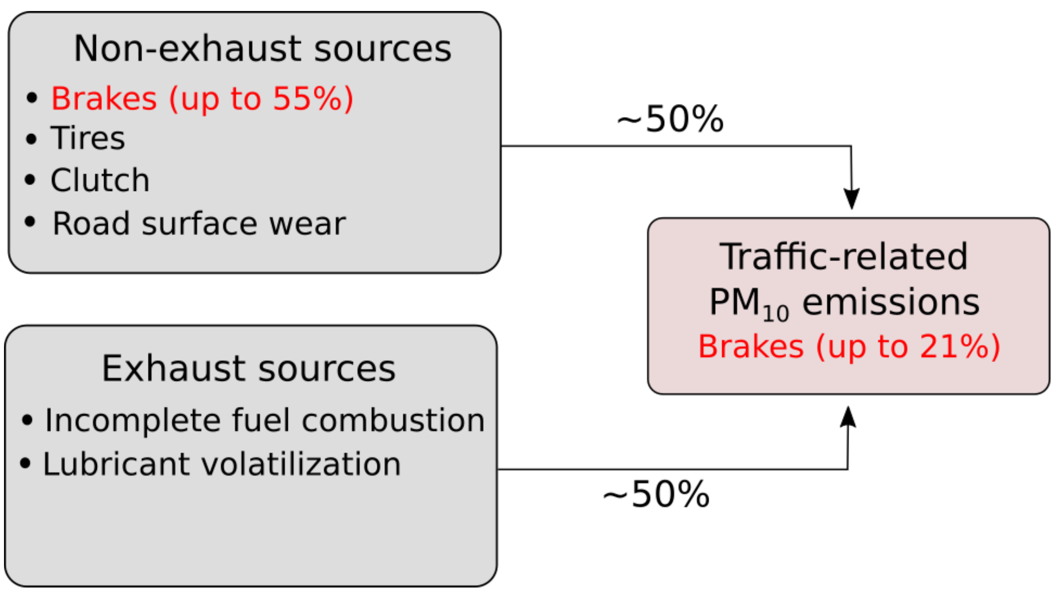

Figure 2.3. *Relative contribution of exhaust and non-exhaust sources to traffic-related PM_{10} emissions. Source: [Grigoratos and Martini, 2015]*

The relative contributions shown in Figure 2.3 are generally sourced from measurements in urban environments, and it is possible that brakes could contribute relatively more at the base of Teton Pass. However, we note that these percentages are for traffic-related PM_{10} emissions, which are some fraction of total measured PM_{10}. In addition to traffic-related emissions, other common sources of PM_{10} include dust, wildfire smoke, and agricultural / industrial processes (e.g. cooking exhaust). Therefore the relative contribution of brake emissions to total measured $PM_{2.5}$ or PM_{10} is likely much less than 20%, particularly during summer when dust and smoke concentrations can be elevated.

Depending on the goals of the study (see section 2.4, "Sampling and Analysis Plans"), constituents to be monitored for brake emissions should include:

1. $PM_{2.5}$ and PM_{10} concentrations (also may include PM_1 and particle counts)

2. Chemical composition of particulate matter

Chemical composition analysis can identify brake emission tracers, most commonly including Fe, Cu, Zn, Sn, and Sb (Grigoratos and Martini, 2015). These tracers are representative of the composition of both the brake pads and rotors. Details of chemical composition measurement and analysis techniques are included in sections 2.2 and 2.4.

2.2 Instrumentation

- ***What instruments are available to measure brake emission constituents?***
- ***What are the purchase costs for this instrumentation?***

The instrumentation in Table 2.1 includes a selected list of particulate monitors with focus on roadside deployment and portability, single enclosed measurement/datalogging platforms, moderate cost, and high quality. We have included a range of instrument options from Aeroqual, Met One and Grimm. We have not evaluated PM monitors from Thermo Scientific (an additional high-quality manufacturer that could be considered).

In addition to the instruments listed in Table 2.1, a large array of affordable (< $500), portable PM sensors are emerging on the market. These sensors range in quality, and are too numerous to describe here. See the EPA Air Sensor Toolbox (https://www.epa.gov/air-sensor-toolbox) or the South Coast AQMD AQ-SPEC evaluation (http://www.aqmd.gov/aq-spec/evaluations/summary-pm) for more information. The Aeroqual S500 is considered a high-quality option in the affordable/portable sensor class and is included in Table 2.1. However, Table 2.1 is generally focused on higher-end instruments as it is likely that a follow-up study for brake emissions on Teton Pass will require more specific and more accurate data than is available from the affordable/portable sensor class.

With exception to the Met One E-BAM Plus, regulatory grade Federal Equivalent Method (FEM) particulate monitors are not included in Table 2.1 (e.g. Met One BAM 1020; GRIMM EDM180). These monitors cost at least $20,000, require rack-mounting in an enclosed building or mobile trailor, and require specialized expertise for operation, calibration, and maintenance. If future monitoring needs ever warranted deployment of FEM instrumentation for a brake emissions study, it is recommended to contact WYDEQ Air Quality Division or a specialized air quality contractor.

Monitor	PM Sensor	Species	Accuracy	Resolution	Temp Range	Cost	Intended Application
Aeroqual S500 (with $PM_{2.5}$/PM_{10} sensor head)	OPC	$PM_{2.5}$, PM_{10}	± 5 µg/m^3 + 15% of reading	1 µg/m^3	0°C – 40°C	$1,500	Handheld / “hot spot” checking
Aeroqual AQY-1 (includes O_3, NO_2, and $PM_{2.5}$)	OPC	$PM_{2.5}$	± 10 µg/m^3 + 5% of reading	--	-10°C – 40°C	$3,800	“Micro” unit for roadside installation
Aeroqual “Dust Sentry” Pro	OPC* + sample filter	PM_1, $PM_{2.5}$, PM_{10}, TSP, particle counts (simultaneous)	± 2 µg/m^3 + 5% of reading	0.1 µg/m^3	-10°C – 50°C	$ 8,000 - $10,000	Research / “near-reference” monitoring
Met One NPM 2 “Neighborhood” PM Monitor	OPC*	$PM_{2.5}$, PM_{10}, TSP	± 5%	1 µg/m^3	0°C – 50°C	$2,000	Rapid deployment, roadside
Met One ES-642 Remote Dust Monitor	OPC*	PM_1, $PM_{2.5}$, PM_{10}, TSP	± 5%	1 µg/m^3	0°C – 50°C	$3,000	Industrial, real-time, roadside, compact
Met One E-Sampler	OPC* + sample filter	PM_1, $PM_{2.5}$, PM_{10}, TSP	± 5%	1 µg/m^3	-40°C – 50°C	$5,300	Industrial, real-time, roadside, compact
Met One E-BAM, E-BAM Plus**	BAM	$PM_{2.5}$, PM_{10}, TSP	2.5 µg/m^3 or 10% in 24-hr period	--	-30°C – 50°C	$10,000 - $11,000	Research / “near-reference” monitoring
GRIMM EDM164 Mobile Monitor	OPC + sample filter***	PM_1, $PM_{2.5}$, PM_{10}, TSP, particle counts, size/mass dist.	± 3%	--	4°C – 40°C	$16,000	Research / “near-reference” monitoring
SKC Personal Environmental Monitor	Sample filter	--	--	--	--	$1,500	Chemical composition analysis

Table 2.1: *Instrumentation available from select manufacturers for PM monitoring, with priority on moderately priced monitors for roadside deployment. OPC: Optical Particle Counter. BAM: Beta Attenuation Monitor. TSP: Total Suspended Particulate.*
** Uses a near-forward scattering nephelometer with heated sharp-cut cyclone inlet.*
*** Met One E-BAM Plus is FEM-certified for PM_{10}.*
**** The GRIMM EDM164 filter is in-line for the OPC intake, and is not a dedicated sample filter.*

The last entry in Table 2.1 is a recommended low-cost sample filter for analysis of chemical composition (M. Bergin, personal communication, 2018). The listed cost includes the filter holder (SKC Personal Environmental Monitor), pump (e.g., AirCheck XR5000), and filters. In this method, PM samples are collected on quartz or Teflon filters with pumps running at a fixed flow rate. The samples are then lab-analyzed for chemical composition and mass concentration of each species. This method could be deployed alongside an optical or beta attenuation PM monitor that does not have sample filter capability (further details included in Section 2.4, "Sampling and analysis plans").

- ***What is the range of data quality among these instruments?***

Data quality ranges among the instruments listed in Table 2.1, and can be initially assessed using the listed sensor accuracy. In general, data quality will increase with instrument cost. For particulate matter monitoring, beta-attenuation sensors (BAM) are generally more accurate than optical laser-scattering sensors. However, optical sensors are better at capturing short-term spikes in PM concentration (i.e. increases over 1 to 5 minutes). In-depth review of instrument technical specifications and previous studies can provide further insight into expected data quality. We have avoided listing any instrumentation in Table 2.1 that is known to be "low" quality. The best way to assess data quality is to include regular instrument calibration or co-location with FEM instrumentation throughout an air quality study.

- ***What expertise is needed to operate the instruments and analyze data?***

Most of these instruments could be operated by properly trained "in-house" field technicians employed by agencies such as the Teton Conservation District, without the need to hire specialized air quality contractors. However, depending on staff expertise, available time, and the complexity of the study, hiring a contractor for deployment, operation and maintenance of the instruments may be required. If filter samples are used, a technician will need to change and collect filters on a regular basis (e.g. 24-hrs).

Data analysis can also become an involved and complex task and will likely require expert resources, particularly if any calibration or co-location techniques are employed. If the results from any air quality study are used to guide regulatory action, an expert consultant or appropriate state/federal agency should be contracted for all aspects of the study.

2.3 Results and limitations from the 2018 measurement campaign

- ***How were brake emissions measured in the 2018 TAC grant project by Inversion Labs "Assessing Impacts to Air Quality From Vehicle Emissions in Teton County"?***

Although brake emissions were not directly measured, Inversion Labs measured ambient particulate matter concentrations ($PM_{2.5}$ and PM_{10}) at the base of Teton Pass during two measurement phases in 2018:

1. Winter measurements were completed during 1-2 hour periods on three days (Jan. 24, Jan. 29, March 7), coinciding with morning and evening commuter traffic periods. These measurements targeted roadside emissions at various locations during periods of cold, clear weather and atmospheric inversion. Measurements were completed with the Aeroqual S500 $PM_{2.5}/PM_{10}$ monitor in handheld mode (no enclosure), with data collected at 1-minute intervals.

2. Summer measurements were completed during a 2-week period (July 10 – 24). The Aeroqual S500 $PM_{2.5}/PM_{10}$ monitor was installed in a custom weather-proof enclosure (Figure 2.4) and mounted on a sign post on the southeast corner of the Stagecoach Bar lawn on the north side of Hwy 22 (see cover photo of this White Paper). Instrument height was approximately 4 meters (13 ft), and data was collected at 5-minute intervals.

Figure 2.4: *Custom enclosure built by Inversion Labs for the Aeroqual S500 $PM_{2.5}/PM_{10}$ monitor. Sampling of ambient air through the enclosure wall was enabled with a 1.5 cm length of PTFE non-reactive tubing.*

- ***What are the overall results of the study?***

During **winter measurements**, $PM_{2.5}$ and PM_{10} levels are mostly very low for all periods and locations, with exception to the evening of March 7 which shows spikes to slightly higher concentrations. A factor that may help support clean PM conditions during winter is snow cover on roads and surrounding terrain which prevent excessive dust production compared to summer. See the results and discussion in Section 3.1.3 "Base of Teton Pass (Wilson, WY)" in the final report for more information regarding winter measurements (Wright, 2019).

During **summer measurements**, $PM_{2.5}$ and PM_{10} show overall low levels, with the largest spikes to higher concentrations occurring in the afternoon and evening hours. The measured background 24-hr average $PM_{2.5}$ concentration ranges 1-5 μg/m^3, with 5-minute spikes ranging 10-40 μg/m^3. For PM_{10}, background 24-hr average concentration ranges 10-20 μg/m^3, with 5-minute spikes ranging 30-160 μg/m^3. Overall, 24-hr average $PM_{2.5}$ and PM_{10} levels remain far below EPA 24-hr standards, with 5-minute $PM_{2.5}$ spikes reaching "low" to "medium" levels on the EPA 1-minute pilot categories.

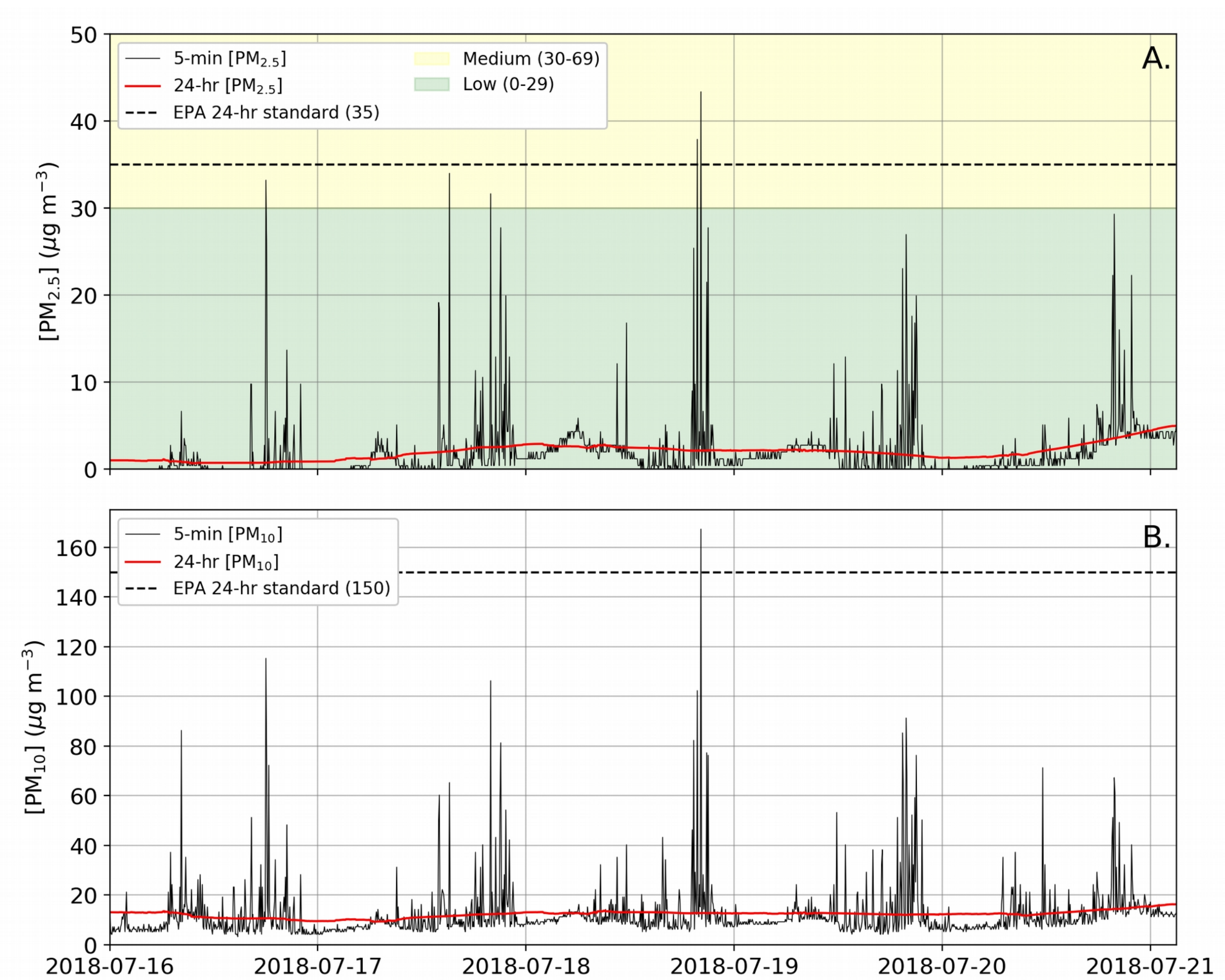

Figure 2.5: *Measurements of $PM_{2.5}$ (Panel A.) and PM_{10} (Panel B.) during July 16 – 21, 2018 at the base of Teton Pass (Wilson, WY). 24-hr averages (red lines) are calculated as a rolling mean from the 5-minute data. Colored bands for $PM_{2.5}$ show EPA 1-minute pilot categories. This period is a representative five days from the two-week measurement duration at this site. Data is corrected using co-location results with FEM instrumentation operated by WYDEQ at the Jackson Mobile site.*

Figure 2.5 shows a 5-day period from the 2-week summer measurement period. Slight increases in $PM_{2.5}$ concentration can be seen during morning commuter traffic, with the largest spikes occurring in the afternoon and evening hours. These spikes are attributed primarily to cooking emissions from the Streetfood Restaurant, due to the distinct timing of the higher concentration periods coinciding with the opening and closing of kitchen operations. Conversation with cooks at Streetfood indicates that the kitchen grill is cleaned and shutdown by 10 pm each night, corresponding with drops in measured PM concentration. In addition, the terrain around the Stagecoach Bar prevents consistent wind direction, where rotors and eddies could disperse cooking emissions over the PM sensor.

Another relatively smaller but significant source of PM is likely diesel truck emissions during acceleration onto Hwy 22 from West St. or Fall Cr. Rd., or during acceleration westbound up Teton Pass. In addition, road dust re-suspended by vehicle traffic likely adds to measurable PM.

Overall, there is no clear evidence for significant impacts from brake emissions at this site. Although there are short-term spikes to moderately unhealthy levels of $PM_{2.5}$, the timing of these spikes dos not correspond to heaviest commuter traffic (instead, the spikes occur mostly during periods of reduced traffic). In the case of brake emissions, we would expect increased concentrations during the morning commuter hours. In addition, because brake emissions are known to likely comprise <20% of measurable roadside PM (Figure 2.3), the maximum PM concentrations that can possibly be related to vehicle brake emissions are very low. See Figure 3.14 in Section 3.2.3 of the final report (Wright, 2019) for the complete time-series of measurements at this site.

- ***What are the limitations of the study?***

Limitations of the measurements include two categories:

1. Sensor limitations

The Aeroqual S500 $PM_{2.5}$/PM_{10} portable monitor proved reliable in co-location experiments conducted at both the WYDEQ Jackson Mobile and Pinedale monitoring sites, when compared to FEM instrumentation (Met One BAM 1020). At the Jackson Mobile site, the $PM_{2.5}$ data showed an R^2 value of 0.64 for 336 hourly data points, and the PM_{10} data showed an R^2 value of 0.65 for 337 points. Overall, we are confident in the general range of PM values measured by the S500 sensor.

However, we note that the sensor is designed for portability, affordable cost, and rapid deployment for “hot spot” checking. The measurements are certainly not as accurate or precise as data from higher-end monitors. In particular, the Aeroqual S500 may suffer from sensor drift over the measurement period (not quantified), and the co-location corrections may not properly characterize the sensor response over the full range of measured PM, which could be non-linear. In addition, we are unable to asses if the custom-designed enclosure inlet had an effect on sample volume or flow rate. In section 2.4 “Sampling and analysis plans” we focus on instrument options with increased accuracy/precision that would be good choices for future monitoring efforts.

2. Siting limitations

The measurement site at the Stagecoach Bar was ideally located in several ways: 1. Located directly adjacent to the highway; 2. Sited at the base of the pass where we would expect maximum brake emissions; 3. Coincides with location of public activity and potential exposure to vehicle emissions.

However, we note that this is only a single measurement location. Although multiple locations were measured during the winter period, a comprehensive study would include multi-day deployments with continuous monitoring at various locations. This would help address issues such as being downwind or upwind of traffic, or the measurements being influenced by other emission sources such as the Streetfood kitchen exhaust.

Additional note regarding potential timing limitations:

Although slight increases in regional wildfire smoke occurred after July 20, the timing of measurements at this site were ideal to capture mid-summer traffic conditions before the influence of wildfire smoke could mask vehicle-related PM emissions. This 2-week period in early July is likely representative of maximum vehicle emission scenarios and is **not** considered a limitation of the study.

2.4 Sampling and analysis plans

- ***Describe options for sampling and analysis plans (SAPs)***

We recommend the following approach for any future sampling and analysis related to brake emissions at the base of Teton Pass. Two major questions should be answered:

1. Are unhealthy levels of particulate matter present at the base of Teton Pass?

The goal of this step is to assess whether there are any measured periods of elevated PM concentration, and how long these periods persist. Measurements should be compared both to EPA regulatory 24-hr standards as well as non-regulatory EPA 1-minute categories to assess if elevated concentrations are considered unhealthy. Measurements should also be made when the influence of wildfire smoke is minimal.

The overall results from the Inversion Labs 2018 TAC-funded study show that unhealthy levels of PM related to vehicle emissions (exhaust and non-exhaust) are **not** present at the base of Teton Pass. Because of the timing of these measurements (before heavy levels of wildfire smoke) and considering relatively good correlation between the Aeroqual S500 and FEM monitors, these results can be used confidently as a baseline for vehicle-related PM conditions at this location.

However, this project was a pilot study conducted by a small team with minimal funding. Due to the limitations listed above (Section 2.3), further investigations may be warranted. If further assessment of brake emissions is pursued, we recommend upgrading to a higher quality PM instrument, and completing measurements at high sampling intervals over an entire summer period at multiple locations.

The Aeroqual AQY-1 or the Met One NPM 2 are recommended as the most affordable entry point for upgrading instrumentation. Instruments such as the Aeroqual Dust Sentry, Met One ES-642 or the Met One E-sampler would be good choices at a higher price/accuracy point if funding allows (Table 2.1). An example sampling plan would include sampling at high resolution (e.g. 5-minute) for 5-10 day periods at multiple locations. Locations could include sites in and around Wilson, both directly adjacent to and away from Highway 22 to characterize concentrations moving away from the roadway. In addition, sites should be considered slightly up Highway 22 (west of Wilson) where more active vehicle braking is occurring (e.g. near the Old Pass Road turnoff).

If elevated levels of particulate matter are detected in measurements, then the following additional question should be addressed:

2. What is the source of elevated particulate matter concentration?

To assess whether vehicle brake emissions are contributing to elevated PM concentrations, the chemical composition of particulates should be analyzed. This can be completed with a standalone filter sample holder (e.g. SKC Personal Environmental Monitor) paired with a PM concentration monitor. This can also be accomplished with an instrument that measures both PM concentration and collects filter samples in one single platform.

We recommend using a singe-platform instrument, since measurement of PM concentration will always be needed in addition to collection of filter samples. This will allow a simpler approach for sampling and analysis of all necessary components. Monitors that include dedicated filter sampling include the Aeroqual Dust Sentry and the Met One E-Sampler (Table 2.1).

Quartz or Teflon filters need to be changed and collected on a regular basis by a field technician (e.g. 24-hr intervals). The filter samples are then sent for laboratory analysis. This analysis is typically done with ICP-MS techniques (Inductively Coupled Plasma Mass Spectrometry), using Principal Component Analysis to determine element ratios and to analyze for trace metals associated with brake emissions. These lab analyses typically cost approximately $150 per sample (M. Bergin, personal communication, 2018). The end goal in this approach is to use element tracers to determine the mass distribution in each sample for brake wear tracers.

In addition to filter sample analysis, expert analysis aimed at identifying brake emissions would benefit from additional information such as PM_1 concentration and particle counts (across multiple size classes). The Aeroqual Dust Sentry Pro may be the single best instrumentation choice for the cost, allowing simultaneous measurement of PM_1, $PM_{2.5}$ and PM_{10} along with particle counts and filter sampling, with a temperature range allowing below-freezing operation (-10 – 50°C). The Met One E-Sampler is more limited (and affordable) with measurement of only one concentration size class at a time (PM_1, $PM_{2.5}$ or PM_{10}) and without particle counts. The E-Sampler also allows filter sampling and has an excellent temperature operation range (low temperature option, -40 – 50°C).

2.5 Previous work

- ***What previous published work has been completed to measure brake emissions in other locations?***

The single best resource we have found for previous work related to vehicle brake emissions is the 2015 review paper by Grigoratos and Martini: “Brake wear particle emissions: a review”. This comprehensive paper covers the current state of knowledge related to brake emissions and includes references to over 100 peer-reviewed studies. This paper is open access and can be downloaded for free at: https://link.springer.com/article/10.1007/s11356-014-3696-8

Despite extensive searching, we were unable to find any previous studies measuring brake emissions in the context of a mountain pass environment with constant vehicle braking. Most previous studies have completed PM measurements in urban environments (e.g. Harrison, 2012), or have completed measurement in a laboratory setting using brake dynamometer assemblies to simulate vehicle braking (e.g. Kukutschová et al., 2011).

We also note that the overall topic of brake emissions analysis is still an emerging field. Grigoratos and Martini (2015) state that “...non-exhaust processes have not yet been adequately studied, and several questions regarding physiochemical characteristics, emission factors and possible adverse health effects of wear particles still remain unanswered (Denier Van der Gon et al., 2013).”

2.6 Health effects

- ***What are the effects of brake emissions on human and environmental health?***

Exposure to high concentrations of both fine ($PM_{2.5}$) and/or coarse (PM_{10}) particles is associated with harmful health effects, particularly those involving the heart and lungs. Cardiopulmonary morbidity and mortality via multiple complex pathophysiological pathways have been associated with increased concentrations of particulate matter (Pope and Dockery, 2006; WHO 2013). Most common are health problems related to oxidative stress and inflammation of the lungs, but can also include cardiopulmonary diseases and lung cancer.

In general, the size of the particles is directly linked to their potential for causing health problems. Fine particles are most dangerous as they can penetrate deeper into the lungs where they can enter the circulatory system (Grigoratos and Martini, 2015). Fine particles also tend to have higher toxicity and longer residence time in the lungs (Pope and Dockery, 2006).

There are no comprehensive studies directly linking brake wear PM with adverse effects on human health (Grigoratos and Martini, 2015). However, a considerable fraction of brake wear particles exist at fine and ultrafine size classes. In addition, chemical composition can increase the toxicity of inhaled particles. Several $PM_{2.5}$ constituents have been seen as responsible for adverse health impacts, with the most important being PAHs, metals and inorganic salts (WHO 2013). Brake emission composition is dominated by metals such as Fe, Cu, Zn, Sn, Sb, and Pb. Therefore, both the size distribution and chemical composition of brake emissions pose a concern regarding potential adverse health effects. For additional information on potential brake wear health effects, see the excellent section on this topic ("Health relevance of brake wear particles") in the Grigoratos and Martini (2015) review paper.

From an environmental perspective, PM generally contributes to decreased visibility, environmental damages such as depletion of soil nutrients and acid rain effects, and material damage such as building discoloration (U.S. EPA, 2016a). There are no known studies directly linking brake wear PM with adverse environmental effects.

3. References

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