Personal Exposure Assessment for Transportation Modes in La Paz, Bolivia

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Abstract

Vehicle emission regulations are sparse and under-enforced in low to middle income countries (LMICs), leading to exceedingly high point source pollutant concentrations in dense urban areas. Although personal vehicle ownership is low in Bolivia, at 68 per 1000 people, there is an abundance of public transportation in La Paz, its capital. Unique to La Paz is the recently installed cable car system: the Teleférico. The main objective of this project was to compare personal exposure to criteria air pollutants on conventional ground based transportation methods - personal car (including taxi), microbus, diesel bus, and walking - to the Teleférico. An additional focus of the project was to demonstrate the effectiveness of low cost air monitoring solutions. Using hand-held, battery-operated monitors for Carbon Monoxide (CO), fine sized Particulate Matter ($PM_{2.5}$) and one of its constituents, Black Carbon (BC), common commuter routes were identified and traversed in each of the available forms of transportation. Data was collected during peak emission time frames, namely the morning commuter rush hours. The results suggest that there is a clear advantage to utilizing the Teleférico as a mode of transport in terms of pollutant exposure as compared to any other form of transport. The data collected was used to determine unit exposure over time for each of the modes of transportation, which allows the average commuter in La Paz to determine the levels of pollutants they are exposed during their commute. The low cost equipment proved appropriate for its purpose, and could certainly be used for similar personal exposure measurements or for stationary air quality monitoring in locations that do not have the resources for laboratory quality instruments.

Background & Introduction

La Paz is located at an elevation of 3,650 meters above sea level in the Western section of Bolivia. The city sits at the bottom of a basin, surrounded by mountains, also known as the altiplano. The La Paz Metropolitan area is comprised of the cities of La Paz, Viacha, and El Alto. El Alto is located along the rim of the basin with an altitude of 4,061.5 meters. The La Paz Metropolitan area is the most populous urban area in all of Bolivia with about 2.3 million inhabitants (IndexMundi). The geography of the area leads to low mixing rates of the air in the bottom of the basin, which coupled with the large and dense population, has led to highly polluted ambient air. This is a concern because the city is unable to expand outwards, and pollution remains in the basin, affecting the health of its inhabitants. Because of its growing population and unique geographical location affecting its air quality, La Paz can benefit from introducing Sustainable Development Goals which monitor and limit urban air pollution.

The Sustainable Development Goals (SDGs) are revised versions of the Millennium Development goals written in 2010. These goals are a UN Member State directive to improve sustainability and quality of life. Sustainable Development indicator 69 focuses on air quality and calls for the monitoring of $PM_{2.5}$ in all urban areas with a population exceeding 250,000 inhabitants (SDSN).

$PM_{2.5}$ is an important pollutant to monitor because of the numerous adverse health effects it has on inhabitants exposed over a long period of time. These particles are so small in diameter - under 2.5 micrometers - that they can penetrate and deposit in the deep lungs. Numerous studies have linked $PM_{2.5}$ to a multitude of problems ranging from heart attacks to increased respiratory disease symptoms. Both the Environmental Protection Agency (EPA) and World Health Organization (WHO) have set standards for $PM_{2.5}$. The EPA standards state that $PM_{2.5}$ should not exceed 35 $\mu g/m^3$ in a 24-hour period and 12$\mu g/m^3$ annually (EPA). The World Health Organization sets $PM_{2.5}$ limits at 25$\mu g/m^3$ for a 24-hour period and 10$\mu g/m^3$ annually (WHO).

The main source of of $PM_{2.5}$ is incomplete combustion (EPA). In an urban environment, the majority of incomplete combustion can be attributed to automobiles. Two other pollutants, which are emitted from this source, are carbon monoxide and black carbon. Carbon monoxide has well-known adverse health effects, and the EPA also sets carbon monoxide limits to 9 ppm for an 8-hour period and 35 ppm for a one-hour period (EPA). Black carbon is a form of PM and is thus formed by incomplete combustion, largely in automobile engines. Even though there are no regulations for this pollutant, it is a very important particle to measure because it is a strong indicator of the influence of automobiles on air quality, and is also very effective at absorbing light energy. This property is a large contributor to the large scale melting of snow and ice around the world.

All three of these pollutants - $PM_{2.5}$, black carbon (BC) and carbon monoxide (CO) - are important to track because they are all products of combustion in car engines, and are thus exposed to people in an urban setting regularly. Although there are vehicle emission regulations in La Paz, they are not strictly enforced. This leads to pollutant levels often exceeding guidelines. Unfortunately, many municipalities in low to middle income countries do not have the resources or training to use scientific air quality measuring equipment because of its high price and thus monitoring can be next to impossible.

With these factors in mind, we designed an experiment that utilized equipment that is cheap, easy to use and requires little resources or training to operate for the monitoring of $PM_{2.5}$, BC and CO. The purpose of this experiment was to analyze commuters' personal exposure to the three chosen pollutants on a variety of transport modes in La Paz, and demonstrate the effectiveness of low cost air monitoring solutions. The types of transit analyzed were the car (including taxis) the microbus, a popular form of public transportation within La Paz, buses that run on diesel fuel, walking and the newly installed cable-car system, the Teleférico. These forms of transportation were chosen because they are they typical forms of transportation used by a commuter.

Because the Teleférico is such a unique and newly installed form of transport, our focus was on comparing the various forms of ground transportation with it in terms of personal exposure to the three pollutants. Since the Teleférico is elevated from the ground and more removed from any direct points of pollution than other forms of transportation, the hypothesis for the experiment was that personal exposure to pollutants will be lower on the Teleférico compared to other forms of transportation used by commuters.

Methods & Equipment

There were four key instruments used in this study, which were all handheld and cheaper versions of more widely accepted, very accurate, and often very expensive pollutant sensors. Particulate Matter ($PM_{2.5}$) was measured using a Dylos: a handheld, battery operated particle counter that operates on the light scattering behavior exhibited by fine particles. Using a single laser outputting light set at 650 nm, a photo-diode is used to detect the scattered light, much like the principle of operation found in expensive particle counters. However, the device only costs $425, while equivalent approved devices can cost over $5,000.

In this device, air is drawn in by a small fan, which unlike a pump system, does not need to be calibrated for volume. It is battery powered and easily rechargeable, however the battery life is only about six hours, while it takes up to 12 hours to become fully charged. This presented a challenge during testing when multiple hours of data were to be collected and recharging for long periods of time was not an option. The Dylos has two size bins into which it sorts the particle count: particles greater than 0.5 µm in diameter and particles greater than 2.5 µm in diameter - from fine particles to the low end of the coarse particle range. Using the difference in these two measurements, $PM_{2.5}$ concentrations can be determined.

The device has onboard memory to store up to 10,000 data points, each of which is a minute-averaged number count of the particles detected, and also contains a timestamp from the onboard real time clock, allowing for precise delineation of events that occur during data collection. This data is read from the device by a simple program provided by the company, which can be saved as a log file (.csv) that can then be opened and manipulated in spreadsheet software (MS Excel) for further analysis.

The output of the Dylos is a number concentration; a simple formula and two assumptions can be used to convert number concentrations ($n(D_p)$) into a more useful mass concentration ($m(D_p)$). Equation 1 shows the formula used, where D_p is the average particle diameter, and ρ_p is the average density of the particles (Environ. Sci.).

$$m(D_p)=16\pi\ D_p\ 3\rho_p n(D_p) \qquad (1)$$

For calculations, a weighted average diameter of 1.29um and a standard density of 1.65 g/cm^3 were used (ScienceDirect). Measurements can be altered drastically by varying these parameters, and it should be noted that $PM_{2.5}$ is generally measured with a smaller lower detection limit, thereby changing the average diameter calculation. The density of particles in this group has been reported in a range from 1 g/cm^3 to 2.3 g/cm^3 (Molenar).

In order to measure the Black Carbon component of aerosol particles, the portable, handheld microAeth was used. This device utilizes the Aethalometer method for measuring BC, which involves air passing through a filter medium that captures suspended particles. Then, the attenuation of an 880 nm LED light through the filter due to particle build up is measured to give a mass concentration output. A clean portion of the filter is used as a reference to provide an accurate attenuation reading.

This filter loses sensitivity as particles build up, so the filter needs to be changed often. These filters can be expensive, however, with the base price for the microAeth only $6,000 instead of $20,000 for a comparable approved Black Carbon monitoring instrument, the cost of this instrument is relatively low.

The device is battery powered and has a lifetime of up to 24 hours running continuously. It can be programed to operate at a flow rate of 50, 100, 150 or 200 mL/min, and measurements can be taken at intervals of every 1 s, 10 s, 30 s, 60 s or 300 s. Both the flow and time intervals can be changed using the microAeth software. The optimal settings for a study can be established based on the environment the device is being used in, as well as what activity is being analyzed. All data can be downloaded whenever the microAeth is connected to the software by using a computer and USB cable. The data file includes the date and time of each data point, attenuation, flow value, temperature, and BC mass concentration in ng/m^3.

Carbon monoxide was measured using the Lascar EL USB, a highlighter sized device that costs only $100, while some high sensitivity CO sensors can cost up to $4,000. It is powered by two half A batteries and can last up to three months.

The device is used by first installing the included software onto a computer. Plugging it into the computer's USB drive and using the software can start the Lascar- either immediately or with a delayed start. It will then run continuously until it is once again plugged into the computer and stopped. The data, which can have a resolution ranging from ten seconds to five minutes and contains CO volume concentrations and a timestamp, can then be downloaded and instantly graphed. This device is both simple and compact, but it is limited to a range between 0.5 and 300 ppm.

Lastly, an Air Quality Sensing Device (AQSD) was used as a long-term sensor on the Teleférico. This device measures humidity, temperature, carbon dioxide, carbon monoxide, and particulate matter, as well as other pollutants that weren't considered in this study. The set-up is built by hand and enclosed in a weatherproof and airtight box with only two holes: one for the inflow of air and one for the outflow. This flow of air is regulated by a PC fan that pushes air out at the outlet of the box. The $PM_{2.5}$ sensor, or Shinyei, as well as the other sensors, are controlled by two Arduino boards that also serve to record the data on an SD card. Measurements are taken with time stamps and formatted into a single spreadsheet with columns dedicated to the different pollutants and meteorological data. The Arduino boards accept power in a recommended range of 9 to 12 volts, with a lifetime dependent on the ampere-hours available in the battery. A large, vehicle 12-volt battery was used during data collection.

Because the study of personal pollutant exposure was the primary objective of this research, methods were determined based on what average Bolivian commutes may entail. Five types of transportation were compared for $PM_{2.5}$, BC and CO: car, diesel bus, walking, microbus, and Teleférico. After arriving in La Paz, the instruments were all tested against previously calibrated equipment to ensure that the high elevation and low atmospheric pressure in La Paz would not significantly affect the accuracy of the data.

Once the accuracy of the data was ensured, testing of the specific transportation methods began. The Teleférico was tested during morning rush hour for multiple hours. This included multiple rides in a single cabin up and down the yellow line (one of the three Teleférico lines), which runs between La Paz to El Alto. Both the Dylos and Lascar CO meter remained inside the cabin collecting data, while tubing was attached to the microAeth, which ran out a window. The windows of the Teleférico cabin remained open throughout the testing period so all instruments were generally exposed to the same air. The AQSD was attached to the top of the cable car, where it remained and collected data all throughout the day.

In the following three days, the other four forms of transportation were tested. The time spent collecting pollutant data on each of these forms of transport was shorter than on the Teleférico, but usually ranged from 20 minutes to an hour. Because there was more freedom in the routes for these modes, the most popular destinations were chosen: most commonly El Alto or San Francisco - the city's center.

Results

When riding the Teleférico, there were large, recurrent changes of altitude between the lower La Paz up to El Alto. Atmospheric conditions can vary with changes in altitude, which is exemplified in Figure 1. This figure shows the temperature and relative humidity data collected by the AQSD over a period of about 13.5 hours: about 6:30am to 8:00pm. Because the AQSD was attached to a Teleférico that was running all day, it was exposed to these regular changes in altitude. The results of this can be seen in the frequent and regular spikes and drops of both the temperature and humidity lines. Consistent with expected meteorological patterns, temperature rises to a maximum in the middle of the day, and begins to drop as night falls, while relative humidity is at a minimum in the middle of the day, and rises again as the day ends. Usually, if taken in one place, these measurements would result in two smooth lines, but at the base of the Teleférico in La Paz, the temperatures were higher and the relative humidity was lower than what was seen in the higher El Alto. These differences in atmospheric conditions during the course of the Teleférico result in the trends seen in Figure 1.

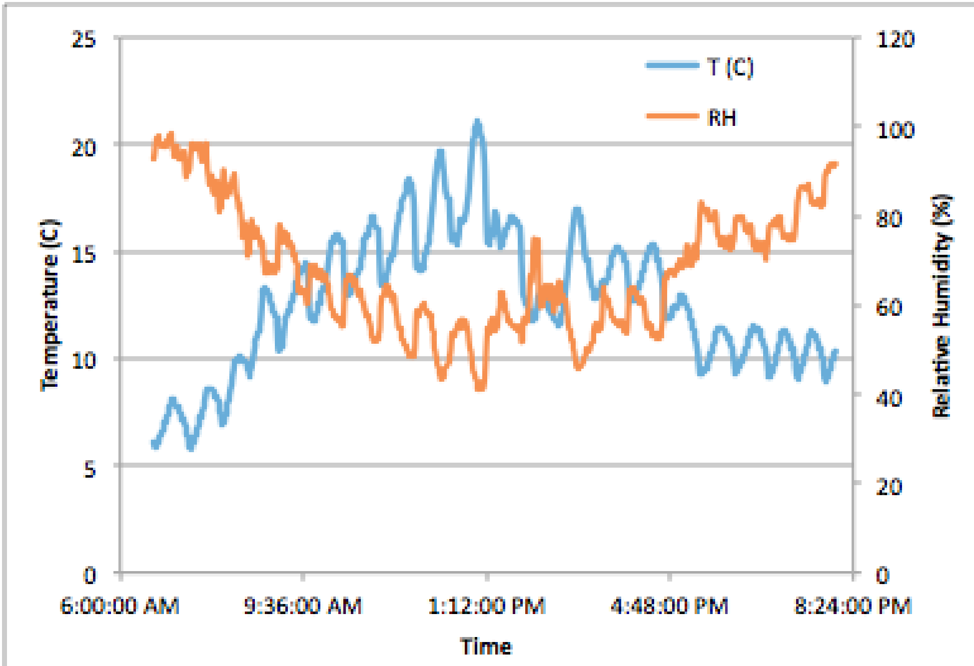

Figure 1: Temperature and relative humidity recorded by the AQSD over 13.5 hours

Temperature and humidity are not the only things that are influenced by altitude. Figure 2 shows the particulate matter data collected by the AQSD during the same time period. It is clear that $PM_{2.5}$ also varies with altitude, as it possesses similar spikes and dips to those seen in the temperature and humidity data in Figure 1. These correlations were seen in the Dylos data as well, but not as strongly, implying that the Shinyei may be sensitive to pressure changes.

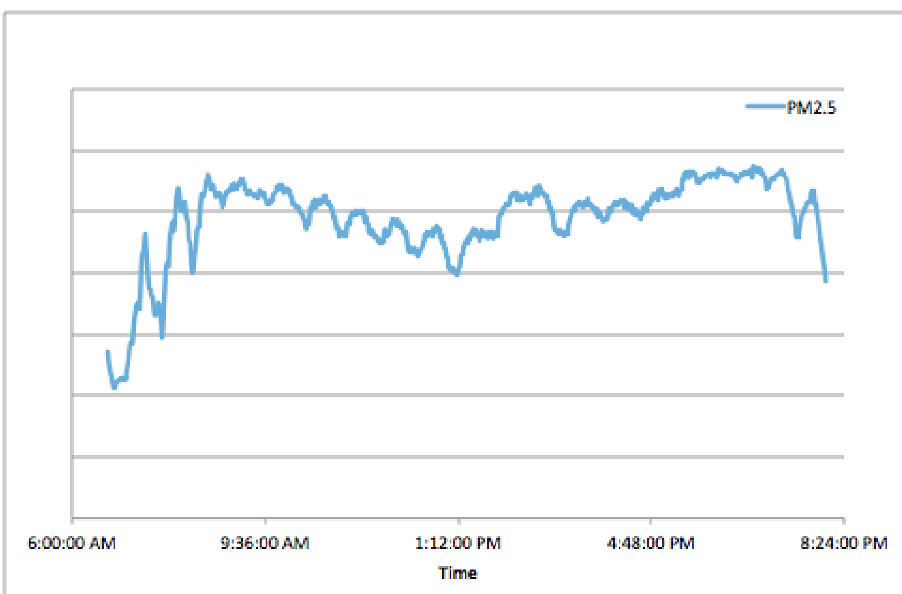

Figure 2: $PM_{2.5}$ measurements from the AQSD over a 13.5-hour period

Figures 3, 4 and 5 present the pollution data collected throughout La Paz on the differing modes of transport. Each data set is formed from the data collected during morning rush hour. However, due to limitations in time and manpower, the data sets pertaining to the diesel bus encompass evening rush hour. This is the only form of transport that does not have morning rush hour data, but it is included for the sake of general pollution comparison.

Figure 3 compares the measured concentrations of BC for the different forms of transport. No international standards are listed for comparison in Figure 3 due to there being no formal standards set for black carbon concentrations. Figure 4 compares the measured concentrations of particulate matter for the different forms of transport. Included in Figure 4 are the WHO standards for $PM_{2.5}$ as a form of comparison. Figure 5 compares the measured concentrations of CO for the different forms of transport. Figure 5 also possesses the National Ambient Air Quality Standards (NAAQS) of carbon monoxide as a form of comparison. These standards pertain to those set by the EPA, and are noted in Figure 3 because the World Health Organization does not have set standards for carbon monoxide.

Figure 3. Black carbon concentration data collected during morning rush hour

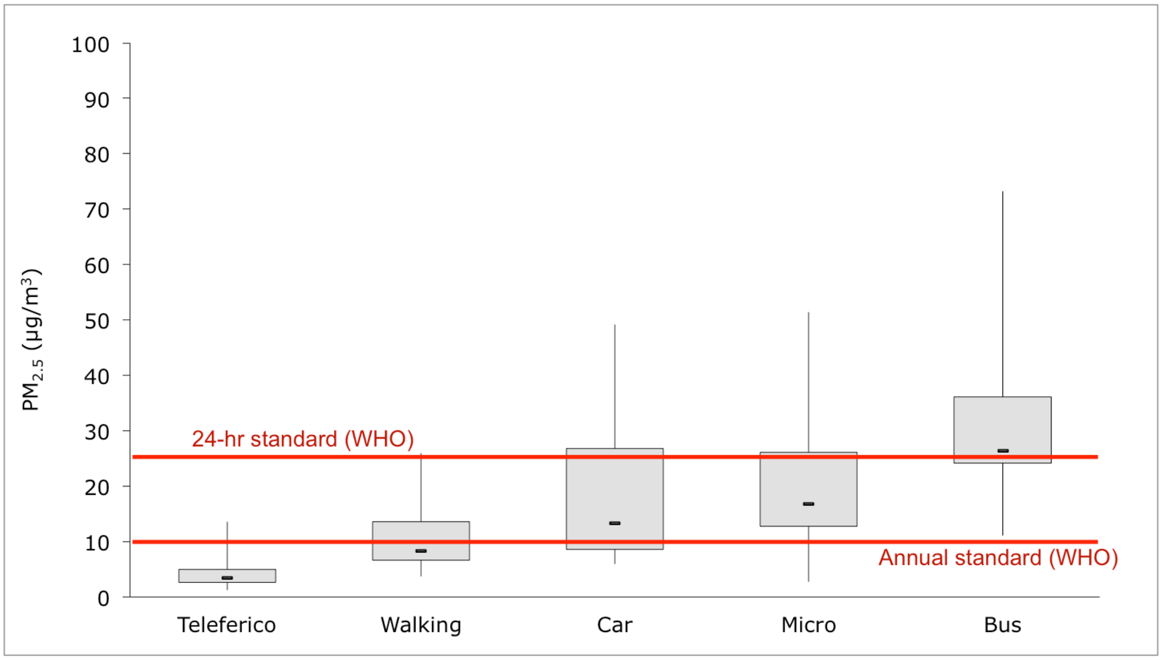

Figure 4. Particulate matter concentration data collected during morning rush hour

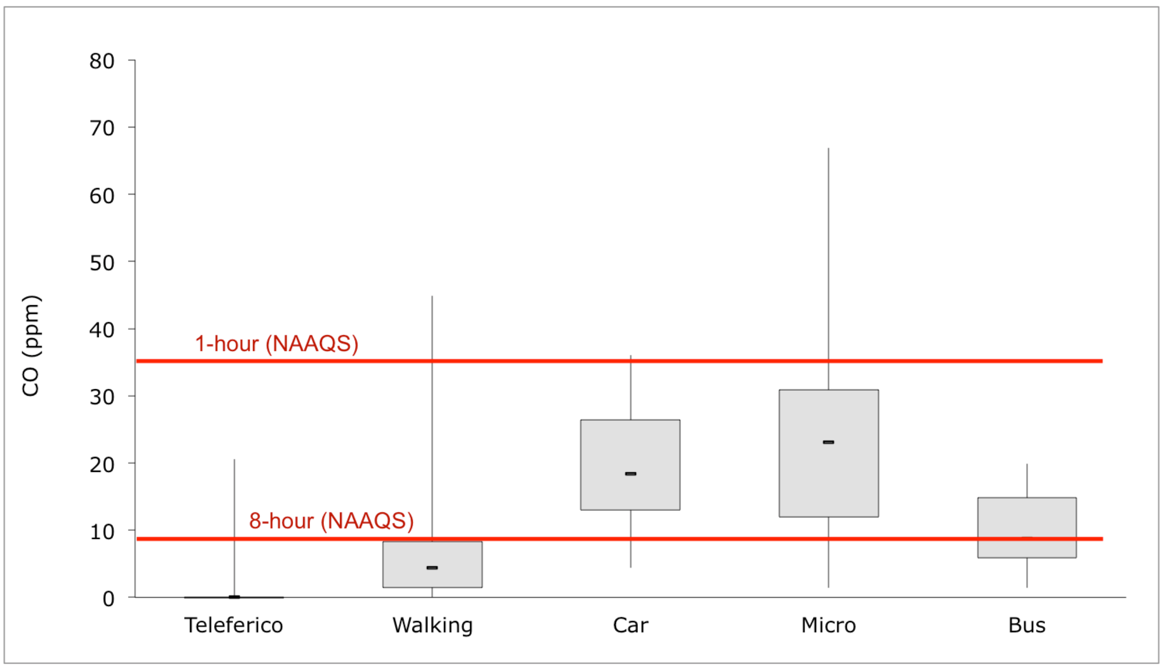

Figure 5. Carbon monoxide data collected during morning rush hours

The CO concentrations in the Teleférico cabin are essentially negligible, both during the morning and evening sample times. Concentrations observed on foot are on average slightly higher than those seen on the Teleférico, but do not deviate as much as measurements taken in motor vehicles. CO levels are within 1 ppm in the personal vehicle and the microbus, both averaging approximately 23 ppm. The diesel bus CO measurements result in an average of 8.82 PPM. BC average observations for the personal vehicle, microbus, and diesel bus are 11.88, 16.73, and 17.14 µg/m3 respectively. These results are in order of magnitude agreement with the $PM_{2.5}$ average observations, which are 24.42, 16.81, and 26.41 µg/m3 for the personal vehicle, microbus, and diesel bus respectively.

Overall, the Teleférico has the lowest concentration values for all three pollutants. Walking as a form of transport has the second lowest concentration values for all three pollutants. However, it should be noted that although concentrations are lower, walking will usually result in a longer commute time. Therefore, walking may expose people to higher concentrations of pollutants over the entire commute. The car, microbus and diesel bus are similar in data ranges overall and possess the same order of magnitude. However, the car has the maximum concentration value for black carbon (147 µg/m^3), the diesel bus has the maximum concentration value for particulate matter (73 µg/m^3) and the microbus has the maximum concentration value of carbon monoxide (67 ppm).

The CO data collected with the Lascar in the Teleférico tended to be very low, or often even 0 ppm. The AQSD has a much more sensitive CO sensor, so it was able to more accurately detect the low CO levels in the Teleférico. The data shown in Figure 6 are the results collected from the AQSD at the same time period during which the Lascar was also collecting data on the Teleférico. The very low CO concentrations measured by the AQSD support the Lascar implications that CO levels can be almost negligible in the Teleférico.

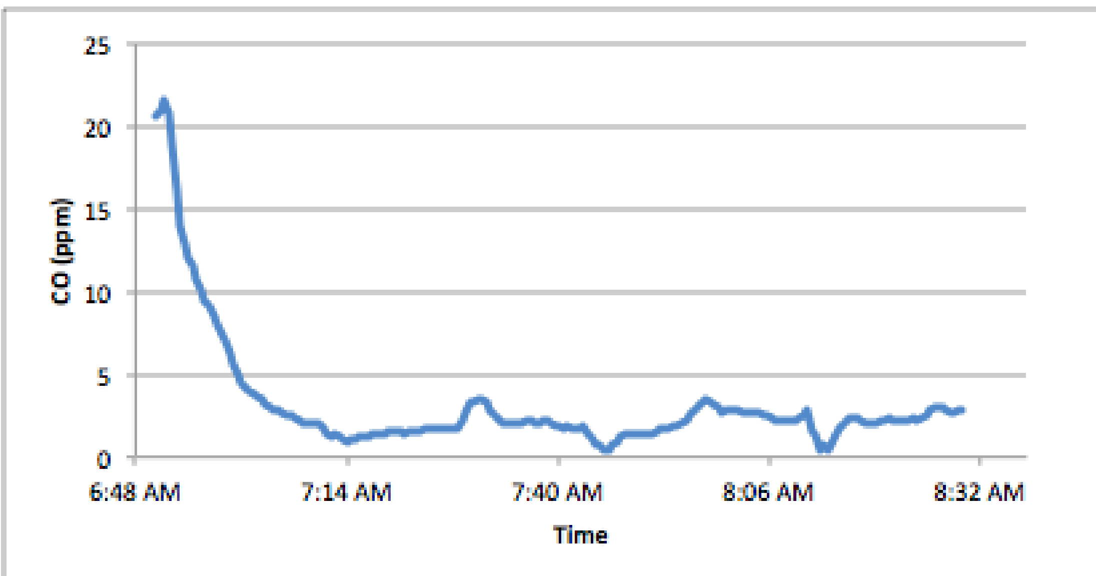

Figure 6: CO morning rush hour data from the AQSD

Personal Exposure Profile

To allow the collected data to be more useful to the general public, a unit personal exposure graph was created for the selected transportation modes, which is shown in Figure 7. The average mass of pollution inhaled per minute is shown for PM and BC, while CO is presented in parts per million as it is a time sensitive pollutant. These values, categorized in terms of transport modes, give the ordinary commuter the tools needed to calculate expected exposure along a certain route. These calculations can in turn lead to commuters making better commute choices based on their personal respiratory health.

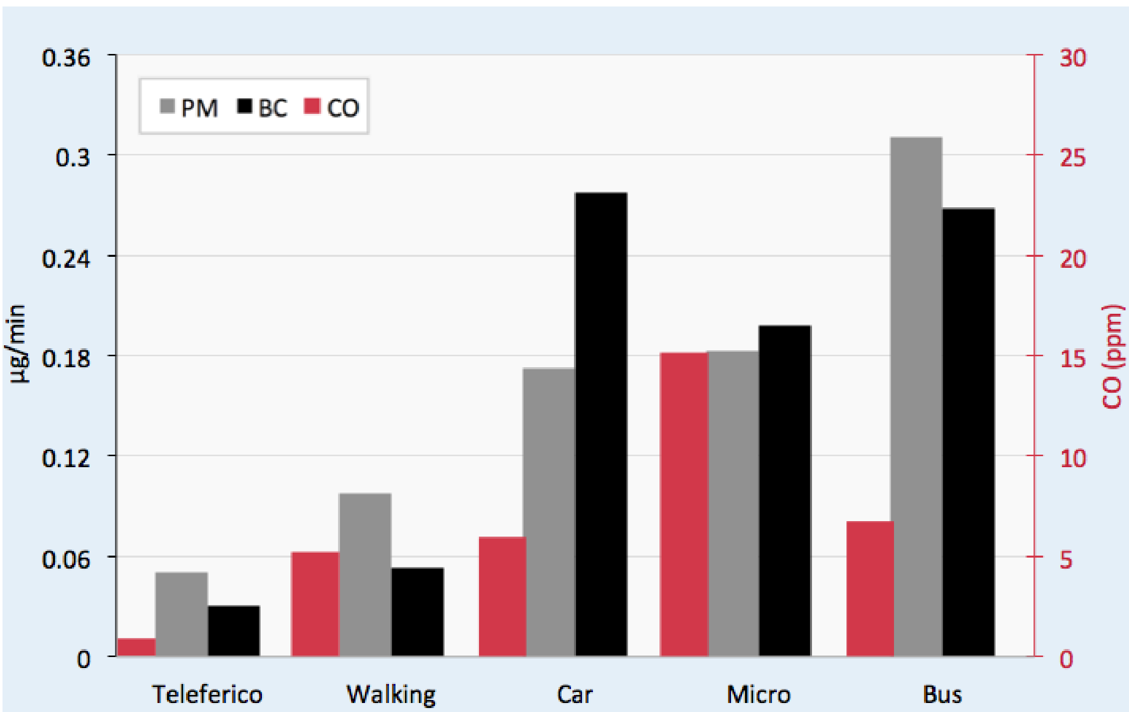

Figure 7. Comparison of unit exposure for all modes of transport

To demonstrate the usefulness of Figure 7, a mock route was chosen for a personal exposure comparison between modes of transport. The route starts at Hotel Calacoto in La Paz, and ends at the El Alto International Airport. Many commuters travel twice daily between La Paz and El Alto for work, thus making comparisons along this route highly significant. For this particular comparison, the Teleférico and car were singled out for the transportation choices along this route.

Using a mapping application (Google Maps), the total travel time along the route by car is determined to be 35 minutes. This leads to very straightforward calculation of multiplying the exposure per minute for a car by 35 minutes for each pollutant. The Teleférico calculation requires a more travel time, as it consists of a combination of transport modes. The mapping application was again utilized to properly divide up the route and estimate time. The first leg of the route consists of walking from Hotel Calacoto to the nearest Teleférico station. This takes approximately 4 minutes. Once on the Teleférico, the total time to travel from La Paz to the El Alto station is 34 minutes. The final leg of the journey involves taking a car from the El Alto Teleférico station to the El Alto International Airport. A map of both routes can be seen in Figure 8 and the results for CO, BC and $PM_{2.5}$ for both the car and Teleférico routes can be seen in Figure 9.

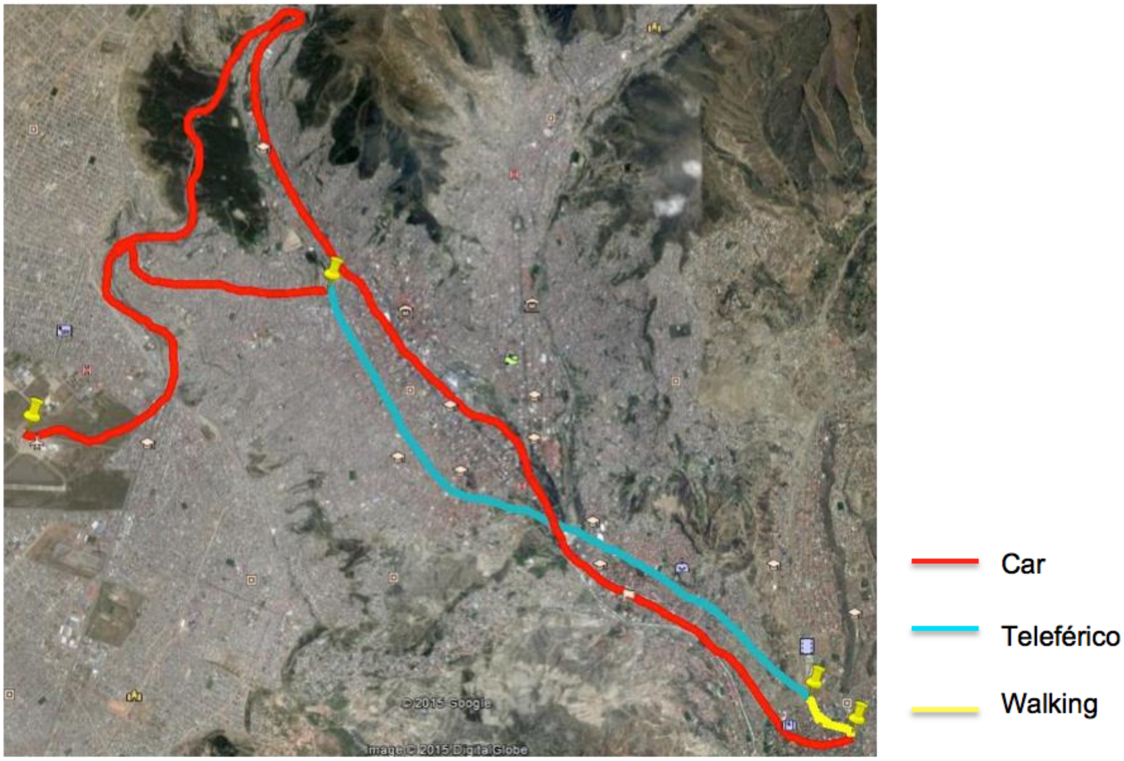

Figure 8. Map showing the Teleférico and car commutes

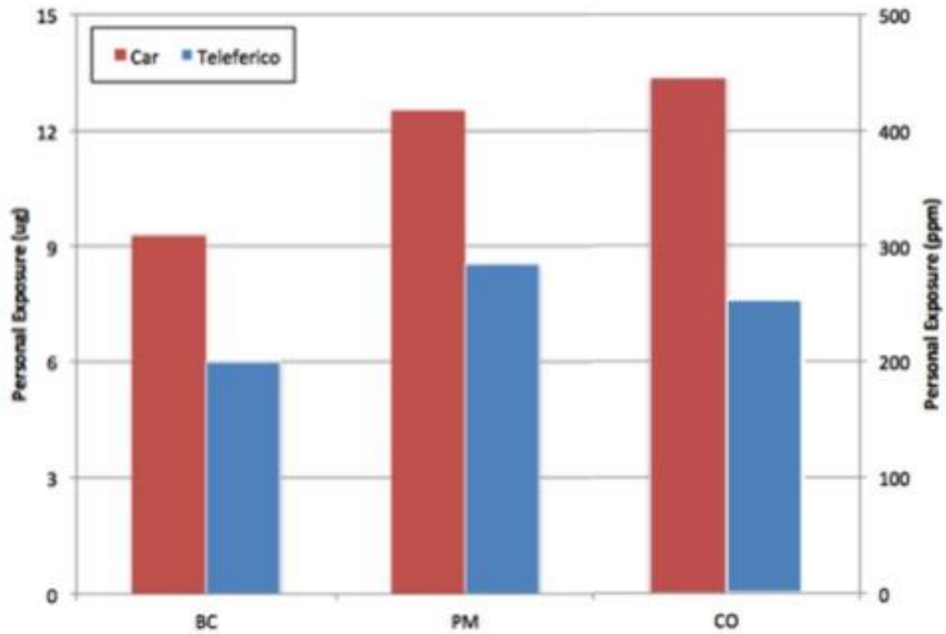

Figure 9. Commute example - Carbon monoxide, black carbon and particulate matter personal exposure comparison

For all three pollutants, the Teleférico route is lower in personal exposure values, even with the inclusion of the walking and car data needed to begin and end the proposed route. This truly gives the citizens of La Paz a way to visualize the exposure they are limiting by making responsible transportation choices along their annual and daily commutes.

Discussion

The results obtained in this experiment have been found to be statistically significant. A non-parametric statistical method, called the Kruskal Wallis test, was used for each different pollutant and the mode of transportation analyzed. For each pollutant and transportation mode the p-value was found to be less than 0.05, which demonstrates that each of the transportation modes is statistically different from each other.

It is believed the results found are largely generalizable in La Paz. The measurements that were taken for ground transportation usually spanned long distances and took a variety of roads ranging from side streets to large thoroughfares. Therefore, the data is a reliable representation of pollutant levels on transportation across La Paz. Some of the general results can hold true outside of La Paz as well. For instance, in most case-scenarios there will be lower exposure to pollutant concentrations when walking as compared to taking a car or bus because walking removes the commuter slightly from the point of pollution. However, precise results in each form of transportation are likely to vary widely from city to city based on geography, culture, city layout and specifications of transportation.

The Healthy Air Campaign in London performed a similar experiment in which concentrations of pollutants while walking, biking, driving and taking a bus along a similar route were compared. The results of this experiment were similar to these in the fact that walking and biking exposed the commuter to the lowest amount of pollutants, despite the increased overall commute time (Healthy Air Campaign).

Some limitations in this experiment were time and equipment availability. As this project was conducted over spring break, there were only five days to collect data. Since the primary focus of this project was pollutant concentrations during rush hour, there were only short gaps of time in the morning and evening where data could be collected. Also, since only two of each pieces of monitoring equipment were available, all modes of transportation could not be assessed simultaneously. The battery life of the instruments was another limiting factor and lead to a lower amount of data collection than was preferred. Despite limitations and further questions, it can still be concluded from this experiment that the Teleférico is the form of transport that will expose commuters to the lowest concentrations of pollutants.

Conclusion

Air quality monitoring is a major component of the planned SDGs, of which the scope is substantially expanded over the previous Millennium Development Goals. Cities of low to middle income countries with a population near or approaching the 250,000 benchmark may not have the resources to adequately monitor $PM_{2.5}$ concentrations; low-cost, easily accessible and easy to use air quality monitoring equipment such as those used here could make pollutant concentration tracking a realistic objective for municipalities such as these. Bolivia alone has eight cities that are either well over or quickly approaching the population cut off, and not all of them have the capability to monitor air quality on the scale that is recommended by the SDGs. The hypothesis that the modern cable car system would expose commuters to lower levels of criteria pollutants was verily confirmed by the observations made along common and highly traveled routes compared to those taken on the Teleférico. It was found that all motorized ground transportation experience similar levels of contamination. Particulate matter and black carbon quantities were found to be significantly lower on the Teleférico than at ground level, although still well below international standards. $PM_{2.5}$ levels near or on roadways often exceeded standards set by the WHO, although walking as a form of transportation allowed for a slight decrease in the measurements. Based on these results, it can be concluded that a larger majority of the commute spent on the Teleférico can be beneficial, and when paired with a pedestrian commute to and from the stations a significant amount of pollutant exposure can be avoided.

Further research would be needed to confirm these results; measurements spanning longer time frames on the order of months to years would be preferable. However, the data collected is valuable for making a basic evaluation of personal exposure for the variety of transportation modes available. Point source pollution from vehicular emissions comprised the bulk of the contamination in La Paz. More rigorous enforcement of the existing emission standards and a more stringent schedule for regulating vehicle emissions would greatly benefit individual commuters and the air quality of the city. Plans to expand the Teleférico already exist, with a tripling of the number of lines proposed. A farther reaching, more expansive mass commuter system in place would provide a valuable resource for the country and set a model for alternative modes of mass transit for other cities facing similar problems. This study has also served as a proof of concept for the application of low cost ambient air monitoring equipment in an urban setting. Although battery life was an issue in this study, if used as a stationary monitoring solution, life of the instruments would no longer be a limiting factor. The devices could certainly have a role in further exploration of personal exposure as well as in a stationary monitoring network in low to middle income countries.

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