The Portland ACE: a Portable, Low-cost, and Networked Device for Assessing Cyclists' Exposure to Air Pollution

Alexander Y. Bigazzi
PhD candidate
Email: abigazzi@pdx.edu

Miguel Andres Figliozzi
Associate Professor
Email: figliozzi@pdx.edu

Portland State University
Department of Civil and Environmental Engineering
P.O. Box 751
Portland, Oregon 97207-0751
USA
Phone: 503-725-4282
Fax: 503-725-5950

ABSTRACT

The Portland ACE (portable, low-cost and networked device for assessing cyclists' exposure) is a prototype sensor system that combines trajectory, local traffic, air quality, meteorology, and physiology data for bicyclists in order to allow direct assessment of the pollution inhalation effects of travel options such as route choice. Testing with high-cost reference instruments on urban streets shows that bicyclists' relative exposure levels on a roadway network can be measured with this low-cost, integrated approach.

Keywords: air pollution; bicycle; exposure; inhalation; mobile sensing

1 INTRODUCTION

There are clear negative health impacts from human exposure to traffic-generated air pollution (Health Effects Institute, 2010), and the health risks could be even greater for bicyclists because of greater respiration during physical activity (Zuurbier et al., 2009). Measuring a bicyclist's pollution inhalation requires simultaneous data on the travel, environmental, and physiological conditions. A review of available products reveals no integrated multi-sensor units for quantifying pollution intake that would be available to the general public. A number of researchers have executed on-road air quality measurements using bicycles, but these platforms are developed *ad hoc*, are high-cost, rarely include physiology, and would be inaccessible to travelers interested in self-assessment or "citizen science", e.g. (Eisenman et al., 2010; Elen et al., 2013; Hatzopoulou et al., 2012; Hong and Bae, 2012; Huang et al., 2012). Several community sensing projects have been initiated, focused on low-cost and/or portable air quality sensors that could be used in large-scale deployment (e.g. Air Quality Egg[1], Common Sense[2], AIR[3], Open Sense[4]). But none use a bicycle-specific platform or include physiology.

The functional objective in development of the Portland ACE was to develop a low-cost and portable integrated sensor system that could simultaneously monitor data for a bicyclist's travel, environment, and physiological characteristics with sufficient precision to assess pollution inhalation differences during travel. This would be a unique tool that would for the first time allow bicyclists to directly measure the exposure impacts of their travel options and allow large-scale deployment of sensor devices for traveler exposure studies.

2 THE PORTLAND ACE

The Portland ACE device contains ten sensors from which data are pre-processed using an Arduino Uno open-source microcontroller. Data are then sent wirelessly at one-second intervals over a Bluetooth modem to an Android device (such as a smartphone) running a custom application. Additional data from the user, Android device sensors, and third-party devices can be integrated through the Android application. A primary function of the system is to integrate and synchronize data from many sensors, providing consistent space- and time-stamping. The system is also modular, allowing different combinations of sensor devices to be used. The device and its development are described in detail in the Portland ACE documentation (Bigazzi, 2013). The documentation is available for download at the Portland ACE webpage, along with the Arduino microcontroller and Android application source codes[5].

---

[1] http://airqualityegg.com/

[2] http://www.communitysensing.org

[3] http://www.pm-air.net

[4] http://www.opensense.ethz.ch/trac/

[5] http://alexbigazzi.com/PortlandAce/

2.1 The Portland ACE Device

The sensors in the Portland ACE device are summarized in Table 1. The air quality sensors are diffusion-based, meaning that air is allowed to pass over the sensors but no air pumping system is used. The prototype design is largely open to the environment, which allows for high air flow. Metal oxide (semiconductor) gas sensors such as the MQ-3 and MQ-7 provide a low-cost and light-weight way to measure gases but are not gas-specific. The optical particle sensors in (Shinyei and Sharp) use infrared light scatter to measure particle concentrations (with an infrared light emitting diode and phototransistor couple). The PulseSensor is a low-cost heart rate sensor that uses a wired clip which attaches to the ear lobe and measures heart rate by sensing capillary blood flow (also detected with a light emitting diode/phototransistor couple).

Table 1. Sensors in the Portland ACE Device

	Sensor	Model	Measures	Price
Trajectory	GPS	Fastrax UP501; MediaTek MT3329 66-channel GPS receiver	Location	$40
	Cycle computer	Electronic Bicycle Speedometer	Wheel rotations; bicycle speed	$5
	Accelerometer	Analog Devices ADXL335	3-axis acceleration	$15
Local traffic	Rangefinder	XL-MaxSonar-EZ0 MB1200	Distance to vehicles; passing vehicles	$45
Air quality	MQ-3	Hanwei Electronics	Alcohol & benzene	<$10
	MQ-7	Hanwei Electronics	Carbon monoxide	<$10
	Shinyei particle sensor	Shinyei PPD42NS	Particulate matter	<$20
	Sharp particle sensor	Sharp GP2Y1010AU0F	Particulate matter	<$20
Meteorology	RHT	Maxdetect RHT03	Temperature; relative humidity	$15
Physiology	PulseSensor	Pulse Sensor	Heart rate	$20

The estimated material cost of producing a Portland ACE device is $175 to $300 per unit, based on retail prices for components. In addition to the sensor costs in Table 1, this estimate includes $100 for electronics components (microcontroller, batteries, voltage regulation, connectors, capacitors, etc.), but excludes any costs for third-party bio-monitors or an Android device. The full prototype version is nearly $300, but excluding the ACE device GPS, rangefinder, Sharp particle sensor, and an extra set of rechargeable batteries would reduce the cost to $175 per unit. For comparison, individual hand-held air quality sensor devices can cost $500-$7,000 per unit. A fully instrumented bicycle with comparable data streams to the Portland ACE using hand-held devices for each pollutant, GPS, speedometer, heart rate, temperature, humidity, etc. could easily cost $10,000 or more and involve labor-intensive preparation and data retrieval procedures. For a comparable price to a single high-precision bicycle data collection setup, Portland ACE devices could be distributed to 50 different travelers.

2.2 The Portland ACE Application

The Portland ACE Android application processes the incoming data from the Portland ACE device, stores it in the Android device's internal memory, and provides a real-time visual display of the incoming data and system functioning (e.g. connectivity, battery status). The Android application allows additional data to be integrated 1) from the Android device's native GPS, 2) through the user interface (i.e. event tags), and 3) from optional third-party bio-monitors[6] that measure respiration and heart rate and communicate with the Android device using Bluetooth. The data storage volume for the combined ACE device and bio-monitor data streams on the Android device's internal storage medium is trivial compared to modern device capacities (<650 kB per hour of data in uncompressed text format).

3 DEVICE TESTING

3.1 On-road Data Collection

An on-road data collection was conducted to test the prototype device and validate the generated data. The Portland ACE device and an Android smartphone (Motorola Droid Razr M) were mounted to the front of a bicycle along with the following reference instruments to measure travel, environmental, and physiological data:

- Airy P311 laser particle counter measuring PM in the size ranges of 0.3, 2.5, and 5.0 μm,
- IonScience PhoCheck Tiger measuring total volatile organic compound (TVOC) concentrations using a photoionization detector,
- Langan T15n electrochemical carbon monoxide (CO) sensor,
- HOBO U12-012 data logger measuring temperature and humidity, and
- CycleOps Joule GPS cycle computer paired with a PowerTap G3 rear hub measuring GPS-based location data and cycle speed through wheel rotations.

Zephyr BioHarness 3 and HxM BT third-party bio-monitoring devices were also tested. The MQ-3 is compared with a TVOC sensor because the MQ-3 has a cross-sensitivity to benzene – a key traffic-generated volatile organic compound). Accelerometer and rangefinder data were not field-validated in this experiment, though they were observed to perform well in basic laboratory tests. On-road data were collected by riding for several hours on a mix of roadway facilities including bikeways and major arterials in Portland, Oregon on July 2, 9, and 11, 2013.

3.2 Sensor performance

Table 2 summarizes the Portland ACE device's sensor performance compared to reference instruments, with correlation coefficients and the number of days with complete data. The low-cost metal oxide gas sensors performed well in representing the variation in on-road exposure concentrations in different locations when compared with higher-cost TVOC and CO sensors (the reference instruments cost around $7,000 and $1,300, respectively). Note that the MQ3 and MQ7 are sensitive to multiple gases, so the reference instruments are imperfect "ground truth" measurements (i.e. perfect correlations would not be expected even in the absence of measurement error). The Portland ACE device's temperature and humidity sensors were consistently within 1° C (temperature) or 5% (relative humidity)

---

[6] The third-party bio-monitors currently implemented are: 1) the Zephyr HxM BT heart rate monitor (retail price around $100) and 2) the Zephyr BioHarness 3 respiration and heart rate monitor (retail price around $500).

of the reference sensors. The Portland ACE device's heart rate measurements using the PulseSensor had "High" performance, but data were occasionally lost because of inconsistent positioning of the device on the ear lobe during bicycling – one shortcoming of using a wired physiology sensor.

Table 2. Summary of Portland ACE device sensor performance

	Sensor	Reference instrument	Performance category [a]	Correlation coefficient [b]	Days
Trajectory	GPS	CycleOps GPS, Android GPS	High	0.87-0.92	2
	Cycle computer	CycleOps, Android GPS, Ace GPS	Medium/high	0.63-0.88	2
Air quality	MQ-3	IonScience	Medium	0.73	3
	MQ-7	Langan	Medium	0.52	3
	Shinyei particle sensor	Airy	Low	<0.05	3
	Sharp particle sensor	Airy	Low	<0.05	3
Meteorology	Temperature	HOBO	High	0.94	3
	Humidity	HOBO	High	0.95	3
Physiology	PulseSensor	BioHarness	High	0.82	1

[a] Based on correlation coefficients with reference instruments, where "Low" is <0.5, "Medium" is 0.5 to 0.8, and "High" is >0.8

[b] Calculated using 1-minute aggregated data for all but the trajectory sensors, which are compared using second-by-second speeds

Only the Portland ACE device's particle sensors had "Low" performance in Table 2, true for comparisons of all 3 particle sizes. These low-cost sensors might not be sensitive enough to measure the variation in on-road PM concentrations, or they might suffer from dominating interference from on-road ambient light variation or vibration. The Shinyei sensor uses a heating element to create an updraft for airflow, making interference from wind and temperature variability likely during outdoor travel. Other research showed poor performance of the Sharp sensor for high resolution measurements, even in indoor tests (Budde et al., 2012).

Overlaying the three sets of GPS data on street maps showed higher precision for the Android and CycleOps GPS devices than the Portland ACE device, as well as quicker satellite fixes (satellite fixes took up to 10 minutes after power-on for the Portland ACE device). The Portland ACE-device GPS data were still sufficient to determine the route of travel (visually identify the traveled roadway). The travel speed as identified by the GPS receivers was noisier than the cycle computers, and the Portland ACE's GPS-based speed was the least accurate of the speed measures, though it still represented the travel speed well enough for most applications.

3.3 System Performance

The overall system performed well during on-road testing, maintaining communications and data logging between the Android application and the Portland ACE device and third-party bio-monitors without interruption throughout all of the tests. The Portland ACE device functioned for 4 hours on one set of rechargeable batteries, though the reference voltage for analog sensors attenuated after 3.8 hours. The rechargeable batteries are easily field-replaced for another 3-4 hours of readings. The other system elements (Android application, Android GPS, and bio-monitoring device) continued to function and log data even after the ACE device lost power. These power conditions are considered sufficient for most applications, as data collections longer than about 3 hours would require breaks for the riders.

The Portland ACE system was shown to successfully measure and combine travel, environmental, and physiology data. Figure 1 is an example of the type of information that can be gained from integrating these sensors. Figure 1 shows second-by-second data from a 7.9 km (4.9 mi) bicycle trip along an arterial starting from an inner commercial/industrial area (from right to left) on July 11, 2013, with the measured exposure concentration (from the MQ-3) shown as the pin height and the bicyclist's measured respiration rate (from the BioHarness) shown as the pin color (with lower to higher rates shown as red-yellow-orange-green). Exposure "hot-spot" areas with jointly higher respiration and concentration values can be identified by tall green pins. The sample trip in Figure 1 starts on the right side with high concentrations but relatively low respiration in the commercial/industrial area. The largest exposure "hot-spot" occurs after crossing SE 39th Ave (marked on the figure with a red box). This location has high traffic volumes and an upward grade, where we would expect both greater vehicle emissions and greater bicyclist exertion.

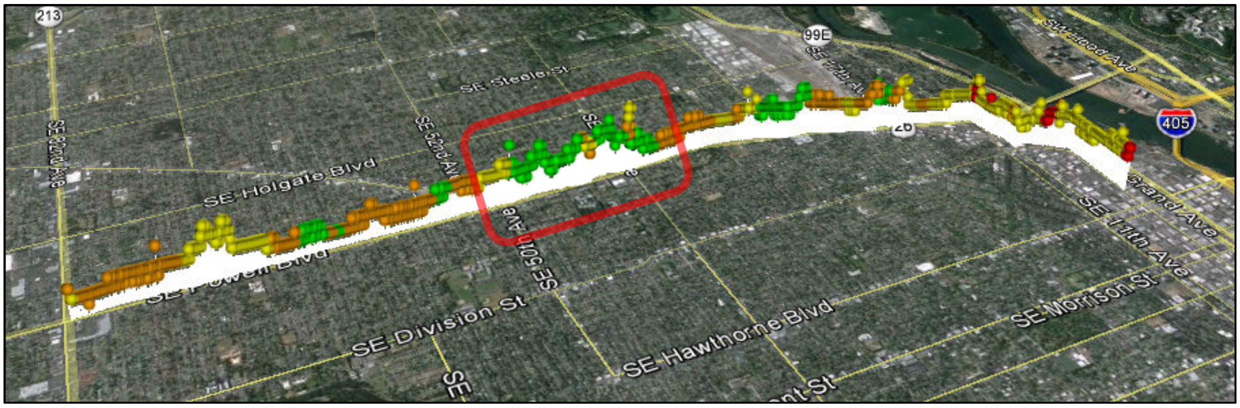

Figure 1. Example of the Portland ACE system integrating travel (location), environmental (gas pollutant concentration as pin height), and physiology (respiration rate as pin color, where green is high) data; exposure hot-spots can be identified by tall green pins (such as outlined in red)
(map imagery from Google Earth)

4 CONCLUSIONS

This paper describes the development of an integrated sensor device for measuring bicyclists' exposure to air pollution that is portable and low-cost: the Portland ACE. The device is small and light enough to mount easily on a bicycle, can be assembled for less than $200, and integrates into a sensor system with an Android device and optional third-party bio-monitor devices. The Portland ACE provides a uniquely easy and accessible way to integrate travel, environmental, and physiological data for bicyclists, in order to estimate pollution intake during travel.

The Portland ACE device sensors performed well overall when compared to higher-cost reference instruments. Trajectory and meteorology data were consistently reliable. The metal oxide gas sensors successfully captured much of the variability in on-road TVOC and CO concentrations, though the PM sensors did not. The integrated pulse sensor performed well, but with reliability issues. Plans for further development of the Portland ACE include a more rugged enclosure for improved on-road durability, real-time data uploading to cloud storage including a web-map interface, and further validation checks with pilot users.

Because low-cost sensors are used, the potential applications for the Portland ACE would favor cost, portability, and data integration over precision of the measurements. Some examples include a commercial product for bicyclists to self-assess pollution hazards and public health projects to map urban air quality and exposure risks with distributed sensors. A wealth of data collected by this device could allow more detailed and comprehensive models of personal exposure in transportation environments for health impact studies. The Portland ACE system could also be interfaced with an individual, high-cost and high-precision air quality instrument to greatly reduce task loads of data collection, providing travel, physiology, and other environmental data streams and requiring synchronization of just the two devices.

5 ACKNOWLEDGMENTS

The authors would like to thank the Innovation Program of the Maseeh College of Engineering & Computer Science at Portland State University for support of this project. Alexander Bigazzi is supported by a Graduate Research Fellowship from the U.S. National Science Foundation (Grant No. DGE-1057604).

6 REFERENCES

Bigazzi, A., 2013. The Portland ACE Documentation: a Portable, Low-cost, and Networked Device for Assessing Cyclists' Exposure.

Budde, M., Busse, M., Beigl, M., 2012. Investigating the use of commodity dust sensors for the embedded measurement of particulate matter, in: 2012 Ninth International Conference on Networked Sensing Systems (INSS). Presented at the 2012 Ninth International Conference on Networked Sensing Systems (INSS), pp. 1–4.

Eisenman, S.B., Miluzzo, E., Lane, N.D., Peterson, R.A., Ahn, G.-S., Campbell, A.T., 2010. BikeNet: A mobile sensing system for cyclist experience mapping. ACM Trans. Sen. Netw. 6, 6:1–6:39.

Elen, B., Peters, J., Poppel, M., Bleux, N., Theunis, J., Reggente, M., Standaert, A., 2013. The Aeroflex: A Bicycle for Mobile Air Quality Measurements. Sensors 13, 221–240.

Hatzopoulou, M., Weichenthal, S., Dugum, H., Pickett, G., Miranda-Moreno, L., Kulka, R., Andersen, R., Goldberg, M., 2012. The impact of traffic volume, composition, and road geometry on personal air pollution exposures among cyclists in Montreal, Canada. Journal of Exposure Science and Environmental Epidemiology.

Health Effects Institute, 2010. Traffic-Related Air Pollution: A Critical Review of the Literature on Emissions, Exposure, and Health Effects (Special Report No. Special Report 17). Health Effects Institute.

Hong, E.-S., Bae, C.-H., 2012. Exposure of Bicyclists to Air Pollution in Seattle, Washington Hybrid. Transportation Research Record: Journal of the Transportation Research Board 2270, 59–66.

Huang, J., Deng, F., Wu, S., Guo, X., 2012. Comparisons of personal exposure to PM2.5 and CO by different commuting modes in Beijing, China. Science of The Total Environment 425, 52–59.

Zuurbier, M., Hoek, G., Hazel, P., Brunekreef, B., 2009. Minute ventilation of cyclists, car and bus passengers: an experimental study. Environmental Health 8, 48.