Measuring Autorickshaw Emissions to Inform Air Quality Policy

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Measuring Autorickshaw Emissions to Inform Air Quality Policy

Mr. Conor Reynolds[1], Dr. Andy Grieshop[1], and Dr. Milind Kandlikar[2] [3]

This document describes the methodology used in a recent project to measure pollutant emission factors and conduct detailed characterization of particulate matter (PM) emitted by "real-world" auto-rickshaws[4].

The measurement campaign was undertaken in the National Capital Region of Delhi, India, in September 2009, in a state-of-the-art vehicle testing facility[5], which is normally used for certification and homologation of new vehicles sold in the Indian automobile market. This was an inherently collaborative research project that will build research capacity and generate knowledge for a network of researchers and in India, Canada and the United States on a topic of global importance: how reducing transportation emissions can have health (air pollution) and climate co-benefits.

Emissions Measurement Campaign

Indian autorickshaws were used as the experimental subject since they are ubiquitous in many cities and provide mobility for short and long distances at any time of the day. With a capacity to carry at least 3 passengers, on average they cover 100 to 150 km per day.

These vehicles are available with a range of fuel systems and engine options in an otherwise identical chassis. The main objective of this campaign was the comparison of emission factors (i.e. emission per unit distance driven or fuel consumed) across different fuels and engine types, and the determination of the variation among our sample of in-use vehicles. We also sought to investigate emissions under different load and speed conditions for a given vehicle. The data analysis of the emission tests will enable us to study the impact of

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[4] Autorickshaws – three-wheeled motorized taxis, found in many Asian cities.
[5] The International Centre for Automotive Technology, IMT Manesar, Haryana, India @ www.icat.in. This paper has not been subject to review by iCAT and therefore does not necessarily reflect the views of the institute. No official endorsement should be inferred.

fuel (natural gas vs. petrol[6]), engine type (2-stroke vs. 4-stroke) and vehicle age/condition on emissions while controlling for other factors such as vehicle type and manufacturer.

The measurement campaign entailed recruiting 31 vehicles and operating them on a chassis dynamometer while quantifying their emissions over 42 tests (eleven vehicles were dual-fuel petrol/natural gas vehicles, which allowed a direct comparison of individual vehicles operating on two fuels). Gaseous (CO_2, CH_4, NO_x, Hydrocarbons, and CO) and PM emissions were measured, using both in-house instrumentation and equipment brought from Canada and the United States (USA).

Figure 1: Autorickshaw in Delhi, India

An emissions model is under development to use real-time data to explore the impact of vehicle operation and drive-cycle choice on emission rates during vehicle certification testing and in real-world use.

Background & Research Needs

Approaches to addressing air quality and climate change impacts of transportation include more stringent emission regulations, improving fuel quality, and the adoption of clean-burning alternative fuels such as natural gas[7]. While such approaches can be effective, institutional mechanisms such as inspection and maintenance programs are also crucial because emission rates from 'real-world' vehicles increase quickly as the engines wear, if they are poorly maintained, or if low-quality fuel is used.

This research project is aimed at examining the impacts of vehicle emissions on both climate change and air quality in an integrated manner. The work is focused on the situation in rapidly-developing Asia; however the research is designed for ease of replication and/or application of the findings in other jurisdictions facing similar air quality management problems. This project aims to contribute to the following questions:

Figure 2: Ambient pollution in Delhi

1. What are the climate and air-quality (and consequently human health) impacts of large-scale adoption of alternative fuels?
2. How do engine technologies, alternative fuel-types (natural gas in particular), and vehicle age and condition affect emissions from real-world vehicles?

[6] The term "petrol" is used throughout this document, but the fuel is more commonly known as "gasoline" or "gas" in North America.
[7] SIM-air Working paper No.8 "Co-Benefits: Management Options for Local Pollution & GHG Emission Control" @ http://www.urbanemissions.info/simair/simseries.html

Box 1: Related publications from the Research Team

Reynolds, C.C.O., and Kandlikar, M. (2008), Climate Impacts of Air Quality Policy: Switching to a Natural Gas-Fueled Public Transportation System in New Delhi, Environ. Sci. Technol. 42(16), 5860-5865.

- An integrated assessment of the climate impacts of using compressed natural gas (CNG) as fuel for public transport vehicles, which was mandated recently in New Delhi, India. The results show that there was a net reduction in greenhouse emissions, constituting a climate benefit. This was primarily due to a reduction in climate-forcing black carbon aerosol. A follow-up study that is in preparation is quantifying the air quality and health impacts of switching to CNG.

Reynolds, C.C.O., Grieshop, A.P., and Kandlikar, M. (2009), "Reducing Particulate Matter Emissions from Buses and Trucks in Asia: A Framework to Assess Air Pollution and Climate Change Co-Impacts," in Low Carbon Transport in Asia: Capturing Climate and Development Co-benefits for COP 15, Earthscan, London, UK (In Press)

- This book chapter provides an overview and analytical framework for assessing options for controlling emissions from heavy-duty on-road transportation sources in developing countries. Many of the technical and institutional options available for this class or sources are also available for light-duty public and private vehicles. In particular, this paper provides a view on assessing vehicles from a 'co-benefits' standpoint, where both the climate-change and local air pollution aspects of emission mitigation options are considered.

Grieshop, A.P., Reynolds, C.C.O., Kandlikar, M., and Dowlatabadi, H. (2009), A black-carbon mitigation wedge, Nature Geosci., 2(8), 533-534, doi:10.1038/ngeo595.

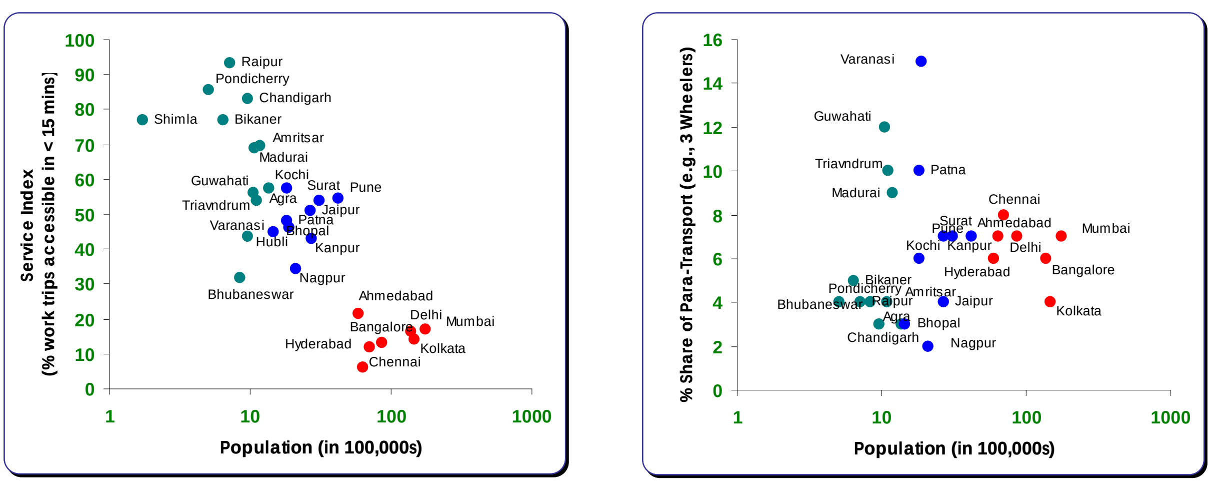
- Further framing of the link between emissions of substances typically considered air pollutants, such as those measured in this study, and climate change mitigation. This provides important insights into the motivation for this work: addressing pollutant emissions from transportation provides a potentially powerful opportunity to align the development aspirations of countries like India with global climate mitigation goals.

Autorickshaws in India

Autorickshaws are a widespread and relatively homogenous vehicle type across many Indian cities (**Table 1**). Their study can provide insights into the impacts of different technological choices, which in turn can be more broadly applied in other areas and to other vehicle types. Autorickshaws fill a vital niche in developing cities between private vehicle ownership and fixed-route and large-capacity public transit systems (i.e. bus and metro). **Figure 3** presents an overview of the share of autorickshaws (para-transit) in 20 growing cities in India, with highest shares measured in the megacities, with some exceptions among the tertiary cities.

Table 1: City autorickshaw fleet for year 2008[8]

City	Fleet	City	Fleet
Delhi	80,000	Bhopal	2,450
Mumbai	108,800	Jaipur	163,200
Kolkata	87,650	Surat	6,250
Chennai	183,100	Pondicherry	800
Hyderabad	96,800	Bhubaneswar	3,450
Bangalore	221,150	Panaji	3,100
Kanpur	1,400	Patna	30,300
Agra	1,000	Kochi	36,400
Pune	34,200	Nagpur	13,850
Ahmedabad	105,900	Guwahati	7,500



Color code: red = mega cities; blue = secondary cities; light blue = tertiary cities

Figure 3: Travel statistics in India[9]

[8] SIM-air Working paper No.24 "Motorized Passenger Travel in Urban India: Emissions & Co-benefits Analysis" @ http://www.urbanemissions.info/simair/simseries.html
[9] Data is sourced from the report "Traffic and Transportation Policies and Strategies in Urban Areas in India" by Ministry of Urban Development, Government of India, May, 2008 @ http://urbanindia.nic.in/moud/theministry/ministryofurbandevelopment/main.htm

Low vehicle cost, flexibility, maneuverability and mechanical simplicity are factors that make these vehicles popular in developing Asia (Iyer, 2003) and in some Latin American countries. In addition, the powertrains in these vehicles are relatively homogenous (usually consisting of simple single-cylinder engines) and quite similar to those used in motorcycles. Different fuel-engine combinations are prevalent in different areas for a variety of reasons. For example, Delhi is dominated by CNG-fueled 4-strokes due to a government fuel mandate, while Hyderabad, Pune, and Bangalore are serviced largely by LPG-fueled 2-strokes. In most cities, the autorickshaw population is dominated by 2-stroke vehicles, because of their light weight and mechanical simplicity, except in cases where policy has favored or mandated the adoption of 4-stroke engines.

Table 2: Basic specifications of 2- and 4-stroke Bajaj auto-rickshaw engines

	2-stroke engine	4-stroke engine
General (both types)	Single-cylinder, spark ignited, forced air cooled	
Engine displacement	145.5 cc	173.5 cc
Bore × stroke	57 mm × 57 mm	57 mm × 68 mm
Max. net power	4.9 kW @ 5000 rpm	4.8 hp at 5500 rpm
Max. net torque	10.8 Nm @ 3500	9.3 Nm at 2500 rpm
Compression ratio	10.0±1 : 1	9.0±1 : 1
Curb weight	335 kg	358 kg

Emissions Testing: Design & Implementation

Sample Size and Selection

An initial plan involved recruiting autorickshaws with 2-stroke and 4-stroke engines using both CNG and petrol fuel, according to the following 2 x 2 matrix (**Table 3**) with a goal to determine fleet-wide emission rates across the range of vehicles operating in Delhi. The results could then be used to assess the impacts of the 2-stroke to 4-stroke and petrol-to-CNG technology switches.

Table 3: Proposed test-matrix for the study

Engine Type	Fuel	
	Petrol	CNG
2-stroke spark ignition	10	10
4-stroke spark ignition	10	10

Budgetary constraints limited us to a total of ~40 tests, so the plan was to conduct 10 tests for each fuel-engine combination. The selection of 10 vehicles per type was influenced by a similar study's finding that 10 vehicles per type should be sufficient to characterize a vehicle population's PM emission rate (Subramanian et al., 2009).

However, early in the planning process it became apparent that 2-stroke petrol engines – although common in many Indian cities – were not available in the National Capital Region (NCR, Delhi urban area). Therefore, in this study we tested vehicles with 4-stroke engines fueled with both petrol and CNG, while those with 2-stroke engines were fueled with CNG.

A total of 42 tests were conducted (40 complete tests, and two pilot tests with a subset of data collected) with 31 auto-rickshaws. The following test matrix (**Table 4**) describes the sample of CNG and petrol autos that were tested. Model year (i.e. vehicle age) ranges were constrained by availability, and are indicated in the table.

Table 4: Final test-matrix for the study, showing numbers of tests for each fuel/engine combination (total: 42 tests with 31 vehicles).

Engine Type	Fuel	
	CNG	Petrol
2-stroke spark ignition	14 autos (1998-2001)	(Not available in NCR)
4-stroke spark ignition	17 autos (11 dual-fuel & 6 CNG) (2000-2009)	11 dual-fuel autos (2000-2009)

2-stroke CNG autos in Delhi were all converted from petrol when the switch to CNG was mandated[10]. In addition, dealers were not permitted to sell new 2-stroke vehicles after 2000 (all 2-stroke vehicles are being phased out in Delhi and some other major Indian cities), so the 2-stroke autos tested were all model year 1998-2000.


2-Stroke

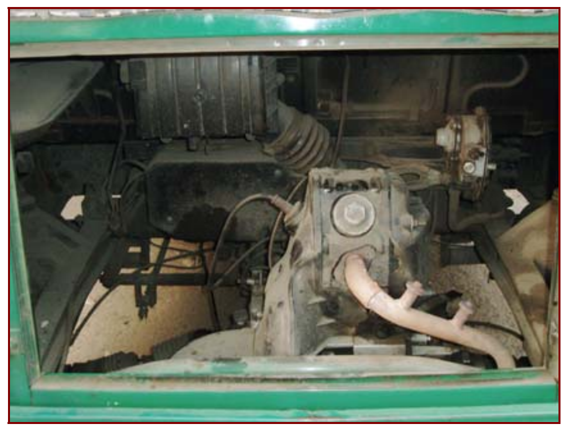

4-Stroke

Figure 4: Natural gas-fuelled autorickshaw engines

4-stroke CNG autos were all model year 2000 and newer. Newer 4-stroke autos are also provided with a small capacity back-up petrol tank (2 liters), but drivers in Delhi rarely (if ever) use this option because CNG refueling stations are now widespread and CNG is significantly less expensive than petrol. For this reason, most of the "dual-fuel" 4-stroke

[10] More on the Supreme Court ruling on CNG conversion @
http://www.cleanairnet.org/infopool/1411/propertyvalue-19513.html
The timeline of implementation (in the transport and industrial sector) and the experience for instituting change which has become a model for other Indian cities, by Narain, et al., 2005, "Who Changed Delhi's Air? The Roles of the Court and the Executive in Environmental Decisionmaking", RFF, Washington DC, USA @
http://www.rff.org/Publications/Pages/PublicationDetails.aspx?PublicationID=17425 Down to Earth, March 2002, "The Supreme Court Not to Budge on CNG Issue" @
http://www.downtoearth.org.in/full6.asp?foldername=20020331&filename=News&sec_id=4&sid=6

autos had to have their petrol systems tuned-up prior to testing, including reconnecting fuel lines, cleaning carburetors and installing new fuel filters.

Recruiting, Transport, and Delivery of Test Vehicles

The project researchers worked with a Delhi-based non-governmental organization (NGO) [11] to recruit auto drivers and their vehicles from Delhi and Gurgaon (a satellite city south of Delhi and closer to the test facility).

While recruiting, a significant challenge was convincing the autorickshaw owners/drivers to participate in the study. Concerns about participating in the measurement campaign included:

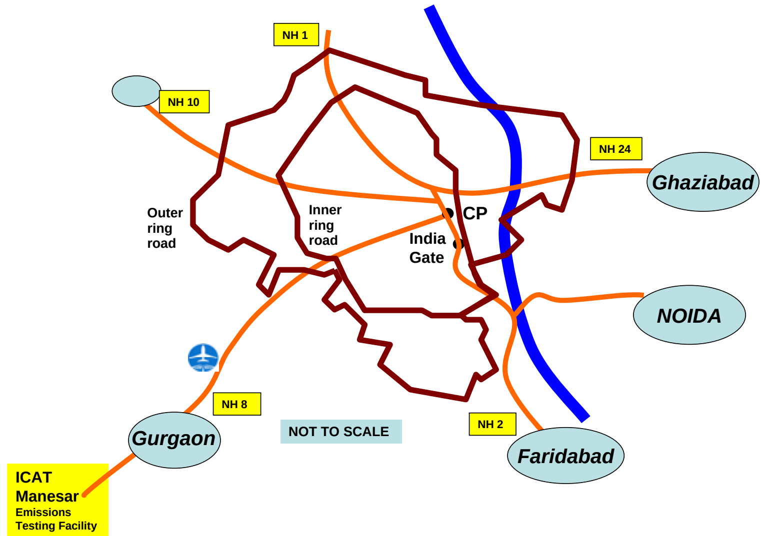


Figure 5: National Capital Region (NCR)

- that their vehicles could be damaged during the testing process, which could be costly for them to repair
- that the payment they would receive for participating would not be adequate
- that they would have to make alternative arrangements for regular passengers
- that they could face problems from officials if their vehicle was found to be a high-emitter
- in the case of drivers who rent from the owners, there may also have been concern that they would face problems from the owners if they participated in such a study

It was essential to engage a trusted local partner who could contact owners and drivers and would be an effective intermediary between the researchers and vehicle operators. The recruitment team liaised directly with the drivers to explain the project goals and requirements, negotiate driver compensation, secure availability of appropriate autos according to the researchers' schedule, and arrange transport of the vehicles to the test facility.

During the testing period, between five to seven vehicles were tested each day (except for the first day of "pilot testing" when two dual-fuel vehicles were delivered and only two tests performed to allow for equipment setup and troubleshooting). Although the aim of the testing program was to measure emissions from unmodified "real-world" vehicles, certain preparations were required to bring the vehicles into the test facility to ensure a base level of function and safety:

[11] Institute for Democracy and Sustainability, headed by Dr. Rajendra Ravi

- the underbody of the autos were professionally cleaned to remove loose dirt, oil and/or rust that could fall off during testing and caused damage to the chassis dynamometer
- major oil and fuel leaks were repaired
- leaks in the exhaust system were patched to ensure that the full emissions were tested and that testing personnel were not exposed to high levels of pollution in the test cells
- safety: brakes, clutch, gears were checked, and had to be functioning correctly
- vehicles had to arrive with a full CNG tank, and a full back-up petrol tank (where applicable).

Figure 6: Autorickshaws being checked prior to testing

When the drivers arrived at the test facility, their vehicles were checked for safety and leaks, and details about the vehicle were recorded: registration/license number, chassis number, and engine/fuel type. Eligible vehicles were tested in random order, determined by a lottery. Note that if any auto had been found to be ineligible for testing (because of safety or irreparable exhaust/oil leaks), the driver is allowed to leave and paid a (reduced) stipend for their participation in the study. Although several vehicles had to be sent for repairs to their exhaust system before testing could commence, no vehicles were deemed unfit for testing during the study.

While testing the autorickshaws, the drivers were accommodated in a waiting room in the building, and provided with lunch. When their particular vehicle was being tested, they were permitted to be present so we could talk to the professional driver if there were any issues with vehicle starting or operation (this was found to be important with the older vehicles, many of which had a hand-lever starting system). The recruitment staff also interviewed drivers during this waiting period using a standard questionnaire developed for a previous study. The questions focus on driver experience, demographics, and socio-economic information along with vehicle fuel usage, distance traveled and maintenance history.

Methodology (facilities, drive cycle, protocol, instrumentation)

The emission tests were conducted utilizing the ~10 minute Indian Drive Cycle (IDC), the standard drive cycle used for emission certification of vehicles for sale (**Figure 7**). Testing was similar to that carried out for vehicle certification except that it included PM sampling via a dilution system. Standard certification of light-duty spark ignition engines does not include PM sampling because PM from these engines is not regulated.

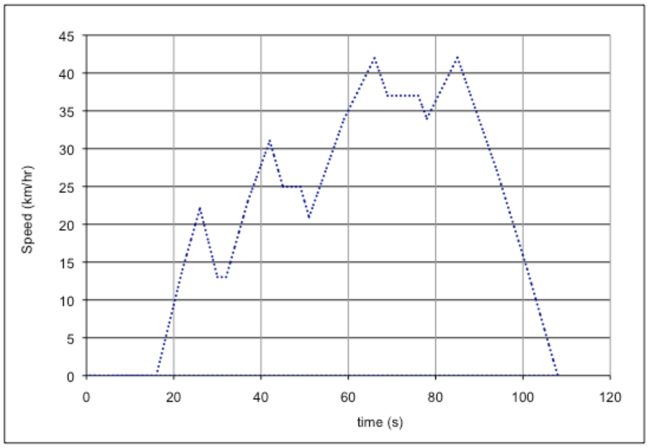


Figure 7: Part of the Indian Drive Cycle (IDC); this sub-cycle lasts 108 seconds and is repeated 6 times to make up the complete IDC

Sampling was via a constant-volume dilution system (CVS) that diluted the vehicle exhaust with varying amounts of filtered air throughout the test cycle. CVS flow rate was varied (between 1 and 10 cubic metres per minute (m^3/min), in 1 m^3/min increments) from vehicle-to-vehicle to maintain diluted PM concentrations of less than approximately 100 mg/m^3 during testing. The nominal CVS setting for a vehicle of this engine displacement is 4 m^3/min.

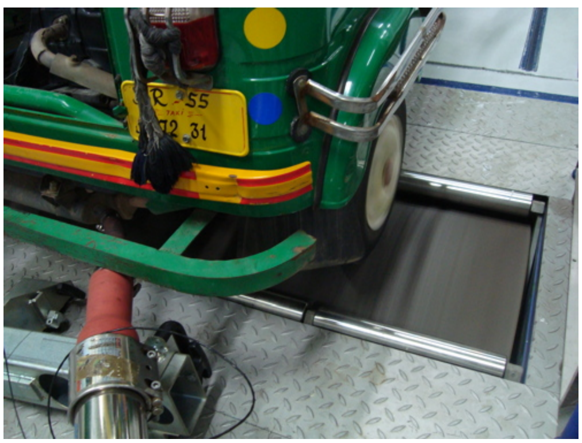


Figure 8: Autorickshaw on chassis dyno

Box 2: Emission testing protocol

When the day's lot of test vehicles are received at the test facility, each vehicle was checked based on the following test protocol:

(A) **Preparation**

- Conduct exhaust, fuel, and lubrication system leak checks
- Repair leaks if necessary/possible
- Conduct safety inspection (e.g. brake, tires, clutch/transmission checks)
- Record vehicle details
- When vehicle is ready to be tested on the chassis dyno, warm up the engine by driving around in the vicinity of the test facility (reduces warm-up time needed on chassis dyno)
- Ensure fuel tanks are full – especially small capacity "back-up" petrol tank

(B) **Warm up and emission testing**

- Install auto on chassis dyno
- Run "warm-up" cycle on chassis dyno (just before emissions testing, for approximately 5-10 minutes)
- During warm-up, monitor PM concentration in real-time (using DustTrak 8520). If concentration exceeds $100mg/m^3$, increase flow rate in dilution tunnel
- Prepare instrumentation (load filters, etc.)
- Conduct test on autos, using IDC cycle

(C) **Idle emission test**

Immediately after the test, while the autorickshaw is still on the chassis dyno, a standard Indian certification test is performed. This test, called Pollution Under Control (PUC) measures undiluted CO and HC concentration using a probe inserted in the exhaust pipe while the vehicle is idling. The instrument used for this purpose was an AVL Digas 444 Analyzer.

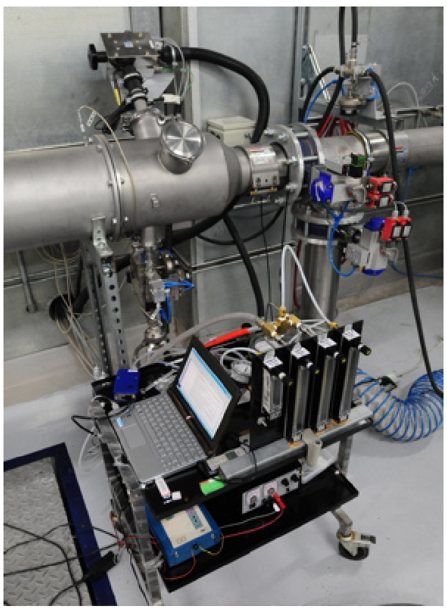
Gaseous Emission and Air Toxic Measurements

Diluted engine exhaust was collected from the CVS into Tedlar sample bags over the duration of the test. The mixed sample was then analyzed to determine the test cycle emissions of each species. In addition, CO_2, CO, NO_x and Hydrocarbons were measured in real-time with one-second resolution. CH_4 data was available as 35 second averages. Aldehydes and ketones were collected in cartridges (Waters Part No. WAT037500) using a Horiba impinger unit, and will be analyzed via high pressure liquid chromatography (HPLC).

PM Sampling

PM samples were collected on two filter trains consisting of 47mm diameter holders, each after a $PM_{2.5}$ cyclone: one with a quartz filter (Bare Q, Pall Tissue quartz), the other with quartz behind a Teflon filter (QBT, Pall Teflon, 2 micron pore size) at a sample flow rate of 20 liters/minute. In some tests, sorbent tube samples (Tenax TA, Sigma Aldrich Part no. 28371-U) were collected downstream of the Bare Q filter at a flow rate of 0.5 liters/minute.

A "dynamic blank" sample was collected following approximately every 10 vehicle tests (i.e. PM filters sampling only dilution air for the test duration, without a vehicle running on the dynamometer). Four "handling blanks" (filters mounted and removed without running a test) were also collected.



PM sampling rig from UBC, Canada, connected to dilution tunnel

Filter pack (white, marked S1) with cyclone (black) below

Figure 9: Setup of sampling and filter collection

A TSI DustTrak 8520 was used to estimate PM concentration in real-time, using the principle of optical scattering. DustTraks are not calibrated for vehicle exhaust (which in any case is highly variable depending on engine type, fuel type, engine load/speed, etc.), so the data will be calibrated in post-processing against the total PM mass measurements obtained from Teflon filter weight.

Finally, a thermophoretic sampler was used to collect particles on 4mm diameter transmission-electron microscope (TEM) grids during each test. Microscopy and image-processing software will be used to characterize typical size and morphology of graphitic carbon (elemental or black carbon) particles, and it may also be possible to estimate exhaust particle size distribution.

PM Analysis and Future Research Needs

In total 50 Teflon filter samples (on pre-conditioned and pre-weighed filters), 100 quartz filter samples and 6 Tenax NA adsorbent tubes were collected during the measurement campaign. Filters were transported back to University of British Columbia in checked airline luggage using a cooler and 'gel' type ice packs, for further analysis (to be conducted in December, 2009).

Teflon filters will be re-weighed to determine absolute PM mass emitted during each test. Organic carbon/elemental carbon (OC/EC) analysis will be conducted on all of the filters. TD-GC/MS (Gerstel) analysis will be conducted on a subset of filter samples and sorbent tubes to generate volatility distributions. Organic marker profiles for the different engine/fuel combinations will be developed.

Results from the analysis will be published in journal papers in 2010.

An expanded version of this study could include other fuel and engine combinations available in Bajaj three-wheeled autorickshaws, shown in **Table 5**. Emphasis in future studies should be placed on fuel/engine combinations that are commonly found in cities in Asia, e.g. diesel, LPG 2-strokes, and petrol 2-strokes. Diesel vehicles would be of particular interest to test in the future and compare with results of the present study, because diesel vehicles have high emission rates of PM, and especially climate-active black carbon particle emissions.

Table 5: Available fuel/engine combinations for Bajaj three-wheeled auto-rickshaws

Engine Type	Fuel			
	Petrol	CNG	LPG	Diesel
2-stroke spark ignition	F	X	F	
4-stroke spark ignition	X	X	F	
Gasoline direct injection 2-stroke spark ignition	F			
Diesel compression ignition				F

"X" refers to fuel/engine combinations tested in this study; "F" refers to fuel/engine combinations that are commonly in-use in Asia, and could be tested in a future study

References

Iyer, N.V. (2003) Role of Three-Wheeled Vehicles in Urban Transportation in South Asia. Smart Urban Transport 2(2).

Grieshop, A.P., Reynolds, C.C.O., Kandlikar, M., and Dowlatabadi, H. (2009), A black-carbon mitigation wedge, Nature Geosci., 2(8), 533-534, doi:10.1038/ngeo595.

Reynolds, C.C.O., and Kandlikar, M. (2008), Climate Impacts of Air Quality Policy: Switching to a Natural Gas-Fueled Public Transportation System in New Delhi, Environ. Sci. Technol. 42(16), 5860-5865.

Reynolds, C.C.O., Grieshop, A.P., and Kandlikar, M. (2009), "Reducing Particulate Matter Emissions from Buses and Trucks in Asia: A Framework to Assess Air Pollution and Climate Change Co-Impacts," in Low Carbon Transport in Asia: Capturing Climate and Development Co-benefits for COP 15, Earthscan, London, UK (In Press)

Subramanian, R., Winijkul, E., Bond, T., Thiansathit, W., Kim Oanh, N. T. Paw-Armart, I. and Duleep, K. 2009. "Climate-Relevant Properties of Diesel Particulate Emissions: Results from a Piggyback Study in Bangkok, Thailand", Environ. Sci. Technol., 43(11), 4213–4218.

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