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Evaluation of Emissions from Asian 2-stroke Motorcycles

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Gaseous and PM emissions of three Class 1 (sub-170 cc) on-highway motorcycles from Thailand that were equipped with crankcase scavenged two-stroke engines were evaluated at the U.S. EPA-National Vehicle and Fuel Emission Laboratory (NVFEL). Very little data currently exists on PM emissions from two stroke motorcycles. There are a large number of two stroke motorcycles in Asia, which appear to be a considerable contributor to PM inventories. This testing was conducted in response to a request from the World Bank for assistance in determining emissions factors for motorcycles commonly used in Asia.

Keywords: Motorcycle, Two-stroke, Emissions, Particulate Matter

1. INTRODUCTION

While small displacement, 2-stroke on-highway motorcycles are uncommon in the U.S., they are used in significant numbers in major cities in East Asia, Africa, Southern Europe and Latin America. Figure 1 shows the proportion of motorcycles in the vehicle population of a number of countries throughout Asia. The proportion of 2-stroke and 4-stroke motorcycles is shown in Figure 2. Motorcycles account for up to 75% of the vehicle fleet in Asia. Of these, approximately 85% are powered by 2-stroke engines.[1] U.S. EPA recently completed testing of three motorcycles that were obtained through an in-use emission-monitoring program in Bangkok, Thailand. The testing was conducted for the "Energy Sector Management Assistance Programme" (ESMAP) in Bangkok, Thailand to assist the World Bank in gaining detailed information on emissions from in-use 2-stroke motorcycles. The data from this test program can be used for emission-factor modeling in Asia. Previous studies have shown that 2-stroke engines can be a significant source of emissions of carbon monoxide (CO), hydrocarbons (HC) and particulate matter (PM).[2,3] There is also evidence of significantly higher emissions of polynuclear aromatic hydrocarbons (PAH) and increased exhaust genotoxicity when compared with exhaust emissions from uncatalyzed 4-stroke-cycle spark-ignition (SI) engines used in similar applications.[4]

2. TEST PROCEDURES

2.1 MOTORCYCLES TESTED

The East Asia Social and Environment Sector (EASES) of the World Bank recruited three motorcycles in Bangkok, Thailand. The motorcycles were shipped to the U.S. EPA-NVFEL facility in Ann Arbor, MI, USA. Pictures of the tested motorcycles are included in Figure 3, and major specifications of the motorcycles are summarized in Table 1. The motorcycles selected for testing represent three of the top four 2-stroke Class 1 motorcycle manufacturers in Thailand. No apparent damage from shipment was noted. The motorcycles were uncrated and assembled by NVFEL staff. Assembly consisted primarily of attaching front wheels and handlebars. The motorcycles were inspected to assure safe operation during dynamometer testing. Modifications were made to attach functional rear brakes to motorcycle "C". One of the primary goals was to run the motorcycles in as close to "as-received condition" as possible. No major repairs were conducted beyond checking basic engine tune-up items (air filter, spark-plugs and plug gap, etc.) as necessary to assure that the motorcycles would start and run. Fluids were checked and added or changed as necessary. Accumulated mileage could not be confirmed due to odometers that had either rolled over (motorcycle A), were replaced at some point in the motorcycles' life, or were nonfunctional (motorcycles B and C). The model years and engine characteristics of the three motorcycles are shown in Table 1.

2.2 FACILITIES

All testing was conducted at the U.S. EPA-NVFEL. The motorcycles were tested using a 48"-diameter single-roll, Horiba electric chassis dynamometer. Exhaust was diluted using a full-flow, low-particle-loss dilution system that has been previously described.[2,5] A PHILCO CFV-CVS was used for flow control of the dilute exhaust, and was operated at a nominal flow-rate of 750 scfm. Table 2 contains a summary of the exhaust gas analytical equipment used.

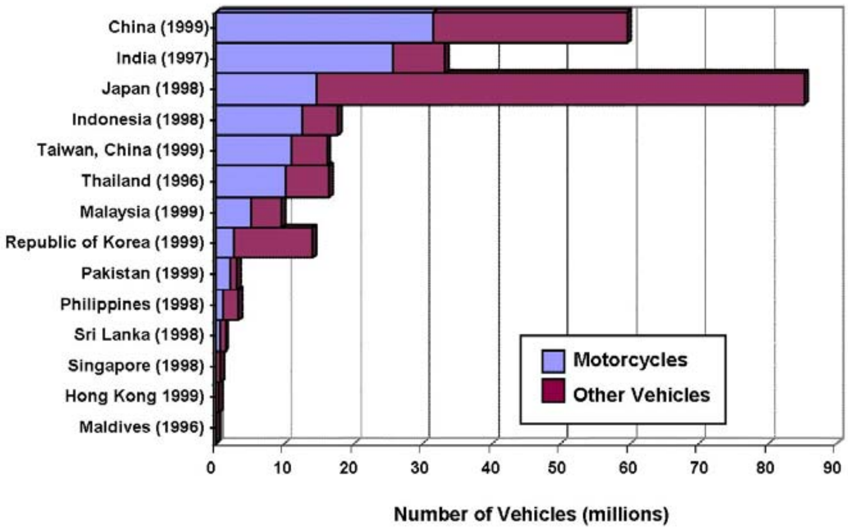

Figure 1: Motorcycle and light-duty vehicle population in selected Asian countries.

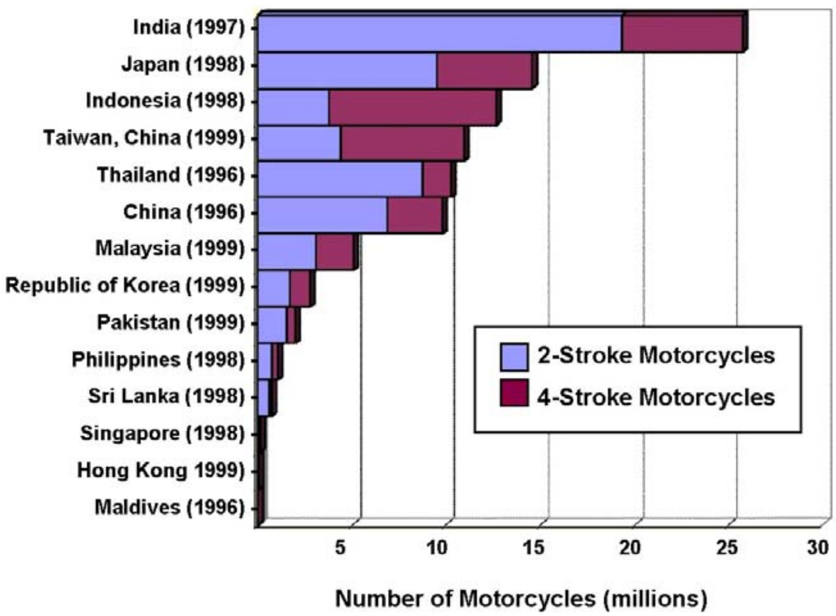

Figure 2: 2- and 4-stroke motorcycle population in selected Asian countries.

Motorcycle “A”

Motorcycle “B”

Motorcycle “C”

Figure 3: Photographs of the motorcycles tested showing some of the set-up details of testing on the single 48” roll electric dynamometer.

Table 1: Motorcycle technical specifications.

Motorcycle	Model Year	Engine Type	Cylinder Displacement	Cooling System Method	Rated Power	Transmission	Inertia Weight (as tested)	Lubrication
“A”	2001	Single-cylinder crankcase-scavenged 2-stroke-cycle	110 cc	Air	N/A	6-speed, manual	180 kg	Automatic
“B”	1995	(see above)	148 cc	Glycol/water	25 kW	6-speed, manual	198 kg	Automatic
“C”	1993	(see above)	123 cc	Glycol/water	14 kW	5-speed, manual	182 kg	Automatic

Table 2: Exhaust gas analyzers.

Bag-sample Dilute Gas Analyzers	Species
HORIBA AIA-23 NDIR	CO
HORIBA AIA-23 NDIR	CO_2
Beckman 400 FID	HC
BECKMAN 951A CLD	NOx
CONTINUOUS DILUTE GAS ANALYZERS	
Horiba FIA-220 HFID	THC
ROSEMOUNT 955 HCLD	NOx
Note: A 191 °C heated sample line was used for sampling from the dilution tunnel to the heated continuous analyzers	

Table 3: Fuel properties.

Test Method	Results
Net Heat of Combustion, ASTM D3338 (MJ/kg)	42.90
Density @ 15.5 ºC (g/cm^3)	0.7432
RON, ASTM D2699	97.0
MON, ASTM D2700	87.6
Olefins (% Vol.)	1.8
Aromatics (% Vol.)	30.6
Saturates	67.6
Sulfur, ASTM D2622 (ppm mass)	31
Lead, ASTM D3237 (g/l-gasoline)	0.004
Phosphorous, ASTM D3231 (g/l-gasoline)	0.0004
Vapor Pressure, ASTM D5191 (kPa)	60.7
Distillation Properties, ASTM D86	
IBP (ºC):	32
10 % (ºC):	52
50 % (ºC):	104
90 % (ºC):	158
End Point (ºC):	203

Table 4: Lubricant properties.

Test Method	Results
Kinematic Viscosity @ 40 °C(centistokes) ASTM D445	47.42
Density @ 15.5 ºC (g/cm^3), ASTM D4052	0.8651
Total Base Number (mg-KOH/g), ASTM D4739	0.9
Total Acid Number (mg-KOH/g), ASTM D664	<0.01
Olefins (% Vol.)	0.0
Aromatics (% Vol.)	59.4
Saturates	40.6
Carbon (% mass), ASTM D5291	86.31
Hydrogen (% mass), ASTM D5291	13.59
Oxygen (% mass), ASTM D5291	<0.05
Nitrogen (% mass), ASTM D5291	0.10
Sulfur (ppm mass), ASTM D2622	

Typically, all of the dilution air for this system is filtered using HEPA filtration on the inlet together with a booster blower. In this case, a fraction of the dilution air was unfiltered and drawn in around the tailpipe of each motorcycle to prevent the sampling system from affecting proper exhaust scavenging. Considering the relatively low ambient concentration of PM within the test-cell during testing (< 50 μg/m3) and the relatively high PM emissions of the tested motorcycles, the effects of the small fraction of unfiltered dilution air on the measured PM emissions were negligible (<<1%), and thus could be eliminated in the final emissions calculations.

2.3 FUEL AND LUBRICANT

The gasoline used for all testing was from a single batch of Indolene™ (Table 3). The motorcycles were equipped with automatic lubrication systems, thus premixing of lubricant with the fuel was not required. Lubricant was provided by the World Bank-EASES (Table 4). It was a standard lubricant formulated for crankcase scavenged 2-stroke engines and commercially available in Thailand.

2.4 TEST CYCLES

Examples of the driving traces used for chassis dynamometer testing are presented in the Appendix. The motorcycles were tested over two chassis dynamometer drive cycles. The U.S. Federal Test Procedure (FTP) for testing of Class 1 (sub-170 cc cylinder displacement) motorcycles was used, which includes a version of the urban dynamometer driving schedule (UDDS) specifically for Class 1 motorcycles.[6] The Class 1 Motorcycle UDDS differs from the more commonly used light-duty vehicle procedures (FTP75/UDDS) in that it has reduced speeds at two sections of the test.[7] The motorcycles were also tested over the New York City Cycle (NYCC).[8] The NYCC contains operation that represents heavily congested urban traffic, with frequent idling and a low average speed. This particular cycle was selected since it appeared to have operational characteristics that were consistent with the manner in which this particular type of motorcycle is operated in large Asian cities.

Table 5: Summary of emissions and fuel economy results over the Class 1 Motorcycle FTP and New York City Cycle.

Motorcycle	**Test Cycle**	**PM (g/km)**	**NOx (g/km)**	**THC (g/km)**	**CO (g/km)**	**CO_2 (g/km)**	**FE (l/100km)**
"A"	Class 1 Motorcycle FTP	0.6 (± 0.2)	0.12 (± 0.11)	19 (± 4)	22 (± 3)	29 (± 2)	5.23 (± 0.7)
"B"	Class 1 Motorcycle FTP	0.3 (± 0.2)	0.02 (± 0.01)	12 (± 1)	13 (± 2)	39 (± 4)	4.06 (± 0.1)
"C"	Class 1 Motorcycle FTP	0.24	0.14	13	7	46	4.20
"A"	NYCC	0.6 (±0.2)	0.07 (± 0.01)	27 (± 2)	21 (±1)	56 (±5)	7.35 (± 0.7)
"B"	NYCC	0.4 (±0.2)	0.05 (± 0.01)	24 (± 1)	24 (±2)	59 (±7)	7.13 (± 0.7)

Notes:

- *The "±" values represent 95% confidence intervals for a two-sided students' t-test with 3 to 4 test cycle replicates*
- *HC emissions are from the continuous heated FID*
- *Fuel economy results are reported as unadjusted test results based on an emissions carbon balance.*
- *Motorcycle "C" experienced a mechanical failure, and thus did not complete sufficient FTP test replicates for calculation of a confidence interval, and did not complete testing over the NYCC.*
- *U.S. FTP emission standards for Class I on-highway motorcycles are HC: 5.0 g/km, CO: 12 g/km. In 2006 the HC standard drops to 1.0 g/km.*

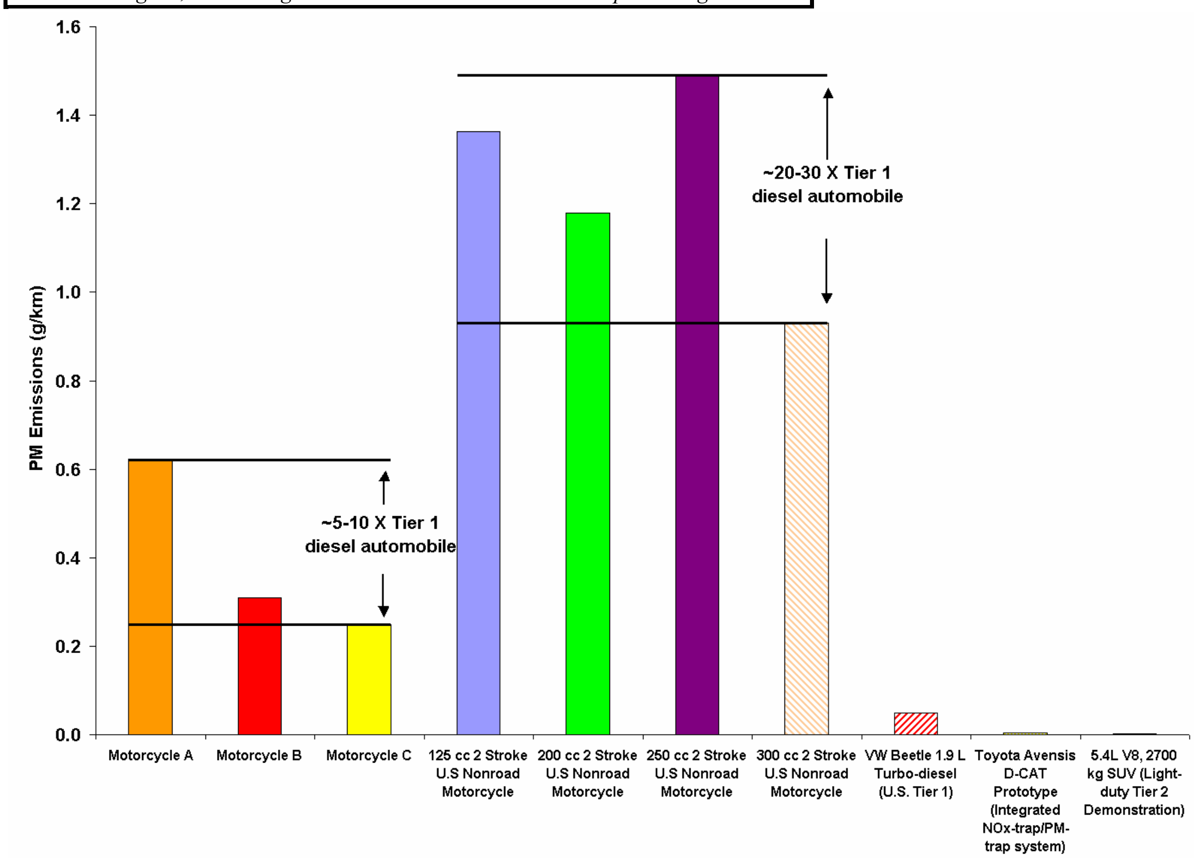

Figure 4: A comparison of PM emissions from the tested motorcycles to that of other motorcycles and light-duty vehicles tested at the U.S. EPA – NVFEL.

3. RESULTS

Emissions and fuel economy results are summarized in Table 5.

3.1 CLASS 1 MOTORCYCLE FTP

The test-to-test variability in NOx and PM emissions measured using the FTP procedures were relatively high. This was due primarily to high variability in phase 1 (cold start phase) emission test results. Phase 1 test results appeared to vary considerably due to poor repeatability in engine start-up performance from day-to-day. Engine start-up and clutch slippage with motorcycle "C" worsened to the point that further testing beyond an initial two FTP tests was not possible and sufficient replacement parts were not available to implement the necessary repairs to continue its testing. The PM, NOx, HC, and CO emissions were comparable between test phases 1, 2 and 3 with the exception of the previously mentioned increased variability for phase 1.

In general, weighted-average FTP emissions of CO, HC, and PM were very high, and were consistent with previously reported results for high-speed, crankcase scavenged 2-stroke cycle engines reported in other U.S. studies for similar applications.[2,3] PM emissions were consistent with previously reported emissions factors for this class of motorcycle in Asia, but HC emissions were from 2 to 4 times higher than HC emission factors that are currently used for Asian motorcycles.[1,9] This is likely due to the use of heated flame ionization detectors (FID) for HC measurement in this and other U.S. studies versus the use of unheated FID or NDIR measurements made elsewhere. Measurement of such high levels of HC emissions was a significant maintenance challenge over the course of the study due to the potential for hydrocarbon hang-up within the heated sample lines and analyzer bench. Such sampling challenges would likely be significantly compounded by the use of non-heated sampling systems and analyzers.

FTP emissions of CO were of the same order of magnitude as emissions of CO2 and were in line with or no more than double the current U.S. Class 1 on-highway motorcycle standard. HC emissions ranged from approximately 2-4 times the current U.S. standard. There is no current PM standard for motorcycles in the U.S. In order to offer a comparison of these emissions with current light-duty passenger car emissions, the HC emissions levels were 200-300 times the NLEV or Tier 2 light-duty HC standards in the U.S. The PM emissions were approximately 10 to 20 times that measured from Tier 1 light-duty diesel emission levels in the U.S. (Figure 4) and 40-100 times the PM standard for light-duty diesel vehicles in the U.S. Tier 2 program.[10, a]

[a] Note that U.S. Tier 1 light-duty diesels are equipped with diesel oxidation catalysts that provide a degree of PM emission control (~10-30%) from pre-catalyst emission levels.

3.2 NYCC

NOx and PM emissions over the NYCC were generally comparable to the FTP results. Test-to-test variability was less than with the FTP testing, which may have been partially due to the lack of a cold-start within the NYCC. CO and HC emissions were substantially higher over the NYCC compared to the FTP results, and fuel economy decreased by approximately 30 to 40%. The results suggest increased in CO and HC emissions from this class of motorcycles when operated in heavily congested traffic.

4. CONCLUSION

The high levels of PM, HC, and CO emissions that were measured from the tested Asian Class 1 2-stroke motorcycles indicate that they are likely to be major contributors to the PM, VOC, and CO inventory in regions where they represent a significant fraction of the total vehicle-miles-traveled. Similar motorcycles represent a large percentage of the in-use population throughout Southeast Asia. Development of effective emissions controls for motorcycles of this type presents considerable challenges. The levels of HC and CO exhaust emissions that were measured would require significant reductions in engine-out emissions before application of effective exhaust catalysts could be considered. The heat-content of the high concentrations of unreacted and partially reacted exhaust compounds (HC and CO) would most likely result in significant catalyst thermal degradation over time via exothermic oxidation within the catalyst unless oxidation efficiencies were limited to very low levels of control.

5. ACKNOWLEDGMENTS

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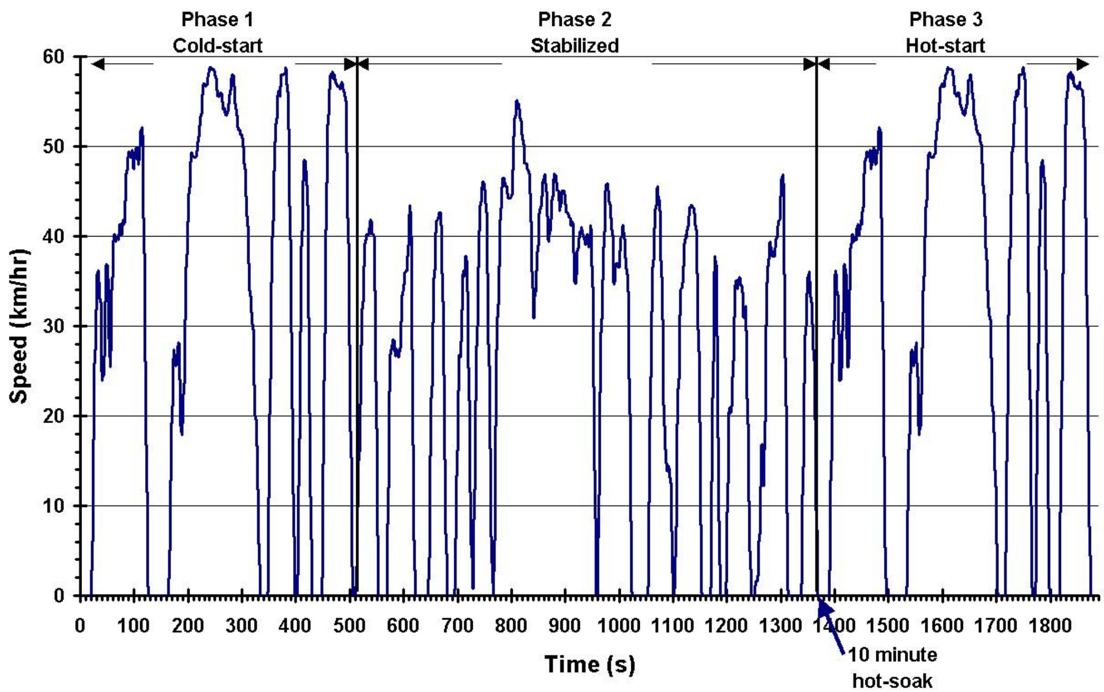
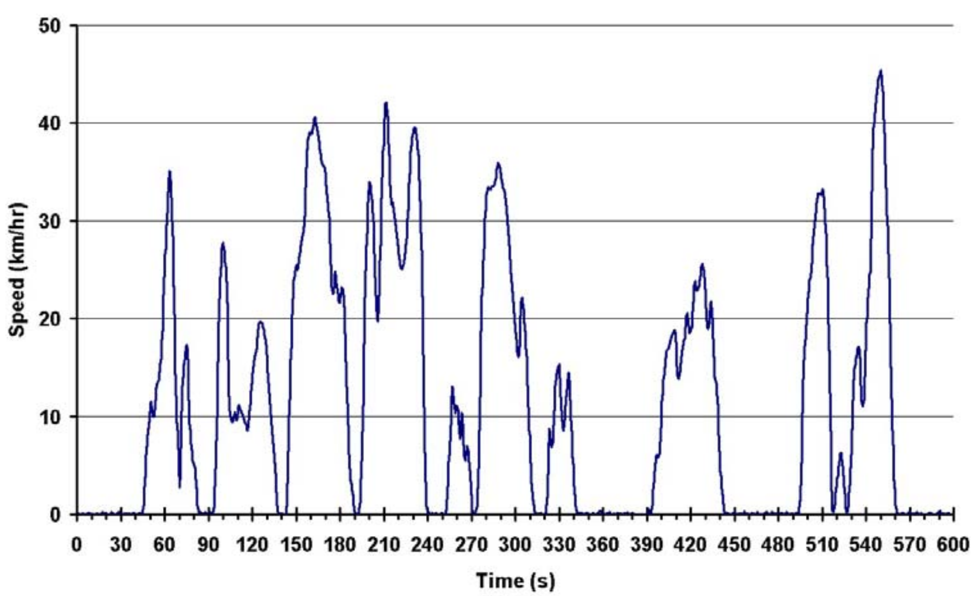
APPENDIX



Appendix Figure 1: Class 1 (<170 cc) Motorcycle FTP Urban Dynamometer Drive Cycle



Appendix Figure 2: New York City Cycle