Onboard Emission Measurement of Motorcycles in Air Quality Management Area of Edinburgh

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Abstract: This article explains the data analysis of onboard measurement using two sets of motorcycles of 1000 cc and 600 cc engine size. Characteristics of instantaneous emissions with time, speed and acceleration have been investigated on the air quality management area in Edinburgh. Average emission factors for CO, HC and NO_X along the corridor have been estimated based on time (g/s) and distance (g/km). Because emissions are primarily affected by speed, therefore a correlation between emission factors and speed has been developed. Using onboard emission measurements, emission can be classified into different vehicle operating modes (idling cruise, acceleration and deceleration). Therefore, models have been developed between time spent in these modes and emission. These types of models are suitable, in evaluation of ramp metering, signal coordination and widely used in ITS.

Keywords: Onboard Emissions, Motorcycles, Speed, Vehicle Operating Mode, Driving Cycle

1 Introduction

Instantaneous onboard emission aims to describe the precise emission of vehicle operating in different modes during a series of short time steps (it may be 1 s intervals or less). Emission can be calculated for any vehicle operating profile. Thus, new emission factors can be generated without the need for further testing. Instantaneous emission can take the dynamics of any driving pattern. Therefore, it can be used to explain the variability in emissions associated with given average speeds. Instantaneous emission allows spatial observation and thus could lead to improvement in prediction of air pollution. Air quality models typically assume that emissions are evenly distributed along the road section, it is therefore likely that such models will under-predict emissions and resulting ambient concentrations at some locations, such as in the vicinity of intersections. In this article, instantaneous onboard emission are discussed along with developing empirical relation between emission and vehicle operating modes and speed.

2 Instantaneous on Board Emission along AQMA

To meet these objectives, repeated numbers of onboard emission measurements were made along air quality management area (AQMA). Overall, the characteristics of the seven sets of data for 1000 cc and five sets of data of 600 cc motorcycles are presented in Table 1. It can be seen that the average speed is higher than those of the car driving cycle (Booth et al., 2001). Booth et al. (2001) reported speeds for EDC of 20 km/h. In our measurements, ambient temperature varied from 10 to 15°C. The distance travelled ranged between 7680.52 and 8180 m. This difference of travel distance was attributed to diversion in following the exact path during the course of the test run: the driver made minor deviations in routes because of route changes announced by ECC for execution of the current tram project across the city centre. It should be noted that due to unavailability of satellites GPS does not provide accurate data, so some test results were discarded.

Fuel consumptions were calculated using the method described by Tong (2000), while total emissions were extracted from the ProBike MicroGas Analyser and expressed as ppm for every 2 s time intervals of

Table 1 Characteristic of test run

S. no	Time of test run (AM/PM)	Engine size (cc)	Distance travelled (m)	Duration (s)	Average speed (km/h)	Ambient temperature (°C)
1	PM	1000	7680.52	1110	24.91	10
2	PM	1000	7830.91	1156	24.39	12
3	PM	1000	8033	1408	20.54	13
4	PM	1000	7988.95	1358	21.18	14
5	PM	1000	7966.22	1282	22.37	14
6	PM	1000	7969.52	1166	24.61	14
7	AM	1000	8056	1062	27.31	13
8	PM	600	8119.47	1374	21.27	10
9	PM	600	7976.56	1088	26.39	12
10	AM	600	8013.08	1298	22.52	14
11	AM	600	8180.35	1358	21.69	15
12	AM	600	8036	1110	26.06	15

Table 2 Results of CO, HC and NO_x emission factors of test vehicle

Engine size	Run no.	Total emission (g/s)			Emission (g/km)		
		CO	HC	NO_x	CO	HC	NO_x
1000 cc	1.0	14.759	0.273	0.082	1.885	0.035	0.011
	2.0	20.432	0.235	0.057	2.709	0.031	0.007
	3.0	16.127	0.196	0.040	4.015	0.049	0.010
	4.0	28.551	0.340	0.081	3.574	0.043	0.010
	5.0	27.918	0.336	0.070	3.505	0.042	0.009
	6.0	22.992	0.274	0.065	2.886	0.034	0.008
	7.0	22.599	0.246	0.048	2.812	0.031	0.006
Average of 1-7		21.911	0.271	0.063	3.055	0.038	0.009
Standard deviation (SD)		5.301	0.052	0.016	0.703	0.007	0.002
600 cc	1.0	12.404	0.305	0.031	1.527	0.038	0.004
	2.0	13.825	0.356	0.037	1.737	0.045	0.005
	3.0	16.329	0.363	0.040	2.036	0.045	0.005
	4.0	14.677	0.317	0.031	1.807	0.039	0.004
	5.0	13.499	0.315	0.023	1.680	0.039	0.003
Average of 1-5		14.147	0.331	0.032	1.757	0.041	0.004
Standard deviation (SD)		1.466	0.026	0.007	0.187	0.004	0.001

the measurement period. These emission values were converted into emission factors and expressed in terms of g/s and g/km as presented in Table 2. The tests were conducted during AM and PM periods: this will affect emissions, because of the difference in soak time of the engine during AM and PM period of driving.

This was part of the limitations of our data collection. It is observed that in general the soak times for AM and PM are 2 and 5 h, respectively. All the emission data were averaged, however, which will impact the accuracy of the results.

3 Average Emissions and Fuel Consumptions

Table 2 shows the HC, CO and NO_X emissions based on distance (g/km) and time (g/s) of different engine sizes for each test drive. The average value as well as SD of the emission are 21.91 (5.3), 0.77 (0.052) and 0.063 (0.016) g/s (or equivalent in g/km) with reasonable SD value. This shows that there was no major fluctuation in driving pattern along the corridor. Standard deviation is a measure of the variability or dispersion of a population, a data set or a probability distribution. A low standard deviation indicates that the data points tend to be very close to the same value (the mean), while high standard deviation indicates that the data are 'spread out' over a large range of values.

Carbon monoxide (CO) is produced because of the incomplete oxidation of carbon during the process of combustion when any fuel is burned. Diesel, bio-diesel, gasoline, propane, natural gas, oil, wood and coal produce carbon monoxide when burned. The highest CO emission was observed in the fourth test run, while lowest CO emission was observed in the first test run. It was noticed that the average total CO emission was 21.9 g/s for 1000 cc, while it was 14 g/s for 600 cc. CO emissions for 1000 cc was 1.5 times higher than 600 cc. The reason for this seems to be the engine size of the vehicle and model year. Vehicle usage and age have significant impact on the emissions (Bin, 2003). The 1000 cc motorcycle was 18 years old as compared to the 600 cc model, which was 5 years old. The 1000 cc motorcycle had a catalytic converter, but this was not very effective in the urban environment due to cold starts, therefore it failed to meet the statutory requirement of CO emissions. CO emissions are also dependent on fuelling calibration and engine size and power (Bosteel, 2005).

Hydrocarbons (HC) are released into the atmosphere as a result of incomplete combustion of fossil fuels as well as fuel evaporation. Details of HC emissions results are provided in Table 2 on a g/km basis. HC emission was not much affected by engine size. HC emissions are primarily associated with early part of the cycle before the catalyst becomes effective. It may be due to the cold start emission of both vehicles. HC levels are also associated with overrun on deceleration. There would be secondary air valve/injection. Control of exhaust emissions depends on the method of injection and the point at which air enters the exhaust system (Bosteels, 2005).

Nitrogen oxides (NO_X) are formed when nitrogen (N_2) and oxygen (O_2) are combined at high temperatures and pressure during the combustion of fuel. Because of the many compounds that are a part of NO_X (predominantly nitrogen dioxide and nitric oxide), the pollutant contributes to a wide variety of health and environmental problems. NO_X is also a main component of ground-level ozone and contributes to global warming. Calculated emission factor of NO_X for both motorcycles are shown in Table 2.

4 Influence of Instantaneous Speed

To investigate the influence of instantaneous speed on emissions and fuel consumptions, records of instantaneous emissions and fuel consumptions were grouped according to the instantaneous speed (Figure 1). The influence of speed was also observed on the different pollutants. It was observed that during 0-30 km/h there is a large reduction in CO, HC and NO_X emissions, then there is slight increase of emission with the increase in speed, for the older motorcycles of engine size of 1000 cc. For the newer motorcycles (600 cc), emissions were found decreasing with increase in instantaneous speed. For the motorcycles (600 cc), the initial CO emissions were very high, possibly due to engine and technology (carburettor) and the cold engine effect. The emission reduced with the increase in engine speed: this shows that burning efficiency improves after certain speed. However, for 600 cc engines a sudden decrease in emissions was observed at 10-20 km/h; this is due to the Euro 2 standard of the motorcycle. Also, newer technology vehicles have lower emissions overall when compared with the older engines.

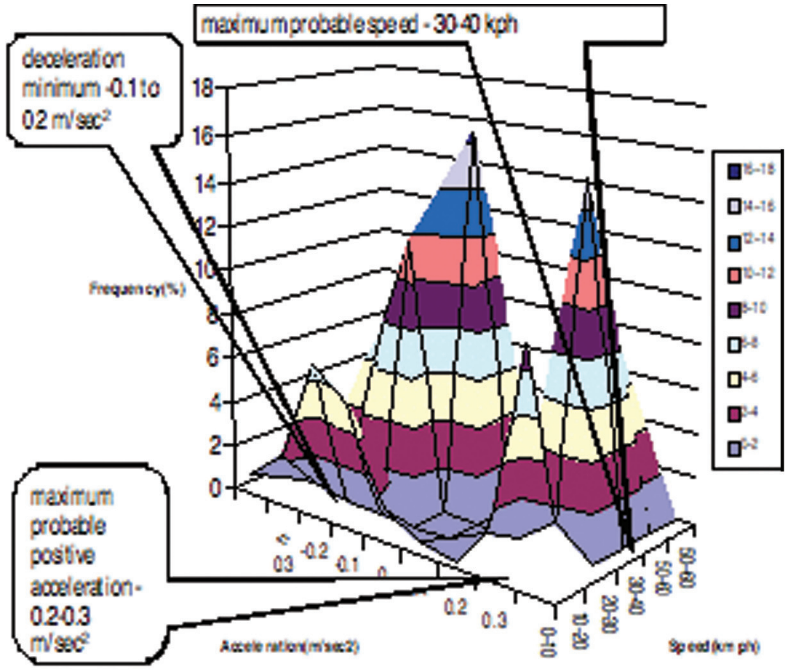

Figure 1 - Speed acceleration frequency joint probability function

Table 3 Influence of instantaneous speed (group in 10 km/h interval) on emission on distance basis

Engine size	Speed (km/h)	CO (g/km)	HC (g/km)	NO_x (g/km)
1000 cc	0-10	25.73	6.43	0.23
	10-20	5.13	1.84	0.06
	20-30	0.02	0.01	0.00
	30-40	2.20	0.66	0.02
	40-50	1.68	0.60	0.02
600 cc	0-10	70.17	1.39	0.04
	10-20	2.55	0.07	0.00
	20-30	1.53	0.04	0.00
	30-40	1.08	0.03	0.00
	40-50	0.94	0.02	0.00

4.1 Correlation Between Emission Factor and Speed

Average speed used as an important factor in emission modelling because emissions are strongly dependent on speed (André and Hammarström, 2000). Average speed is also an important variable in emission modelling because traffic emissions are strongly dependent on speed in a non-linear fashion. In this section, relationships between different emissions and instantaneous speed (grouped into 10 km/h speed intervals) have been developed along the corridor.

The emission model is developed based on the instantaneous speed of motorcycles and emissions. Table 3 shows that generally emissions are higher at the very low speeds, and decreases as speed increases up to 30 km/h, and then emissions start to increase, which indicates that this has implication on speed enforcements for motorcycles to reduce emissions. Furthermore, these empirical formulae have been

Table 4 Regression models for different pollutant emission as function of instantaneous speed

Engine size	(g/km)	Model	R^2
600 cc	HC	$0.0017 * v^2 - 0.1234 * v + 2.4083$	0.8674
	CO	$0.0914 * v^2 - 6.6466 * v + 126.13$	0.993
	NOX	$0.00004 * v^2 - 0.003 * v + 0.056$	0.7439
1000 cc	HC	$0.0109 * v^2 - 0.7423 * v + 12.597$	0.9806
	CO	$0.0473 * v^2 - 3.1167 * v + 51.088$	0.9603
	NOX	$0.0004 * v^2 - 0.025 * v^2 + 0.4326$	0.966

Note: *V* is the speed of motorcycle.

developed to calibrate regression models for different pollutant emissions as functions of instantaneous speed (detailed in Table 4). R^2 is also calculated for each model. In this study, R^2 is found to be greater than 0.86, which shows higher goodness of fit of the data.

Higher levels of NO_X emissions are the result of leaner air/fuel ratios and the resulting higher combustion temperatures. NO_X emissions peak near stoichiometric ratio (chemically balanced mixture of air/fuel ratio). Diluting the air/fuel mixture with exhaust gases reduces peak combustion temperatures and NO_X formation reduces. It reduces up to speeds of 30 km/h, then increases again (see Table 3). Table 4 represent a crude equation of emissions as a function of instantaneous speed based on local traffic conditions in Edinburgh city centre and on selected routes. This could be used as an alternative to the TRL emission coefficient. It is important here to note the need of local emission models for air pollution control authority. Speed is a highly sensitive parameter in emission modelling: inaccurate speed predictions may have a strong effect on predicted emissions. For instance, TRB (1997) conducted a sensitivity analysis on the average speed emission model MOBILE 5 and found that an error of 5 km/h in the estimated value of speed for a freeway caused a 42% difference in CO emission predictions because of the strong non-linear relationship between emissions and speed. There have been efforts to improve estimates of mean link speed from (static) macroscopic traffic models using traffic data that are relatively easy to obtain (Nesamani et al., 2007).

5 Modelling Modal Emissions for Pollutants

A convenient method to characterise vehicle operating modes is to set up a speed/acceleration matrix. With such a matrix, it is possible to associate emissions with speed in each bin/class of range or mode. Collected data were processed and synchronised with analyser data. Furthermore, driving conditions data were classified into four vehicle operating modes in the following criteria based on deceleration ($0 < -0.1$ m/s^2), idling (0-3 km/h), cruising (> -0.1, < 0.1 m/s^2 and > 0-3 km/h) and acceleration (> 0.1 m/s^2).

The modal emission for CO, HC and NO_X are shown in Table 5 for acceleration, deceleration, cruising and idling modes. Higher percentages of total emissions were observed during deceleration and acceleration driving modes for both engine sizes, respectively. Lowest emissions were observed in idling and cruising driving modes. The details are discussed as follows.

5.1 Observed Emission in Deceleration

The EMDC has a frequent number of decelerations. During deceleration modes, the engine does not necessarily generate power. However, the fuel flow rate cannot be stopped immediately when transferring to deceleration modes from acceleration and cruising. Excess fuel thus continues flowing at the early phase of deceleration (Carlock, 1992). The CO emissions of the 1000 cc and 600 cc in deceleration modes were 49-56% of total emission, while it was 45 and 51% of total emissions for HC. NO_X emissions in deceleration mode were 48% and 56.7% of total emissions for 600 cc and 1000 cc, respectively. It appears that NO_X emission for small engine sizes are higher as compared to bigger.

Table 5 Observed total emissions in vehicle operating modes

Engine size	Vehicle operating mode	CO (%)	HC (%)	NO_x (%)
1000 cc	Deceleration	49.28	45.27	47.85
	Idling	2.56	11.61	7.42
	Cruise	5.79	4.85	5.56
	Acceleration	42.37	38.28	39.18
600 cc	Deceleration	56.95	50.95	56.71
	Idling	1.78	3.08	2.89
	Cruise	5.75	5.65	7.42
	Acceleration	35.53	40.32	32.98

5.2 Observed Emission in Idling

The urban EMDC has lower time spent in idling and cruising because of typical driving characteristics. The reason is that Edinburgh has rolling terrain and a SCOOT signal controller system. Apart from that motorcycles can filter into traffic while manoeuvring, so less time is spent in idling mode. As a result, a small amount of fuel is needed to maintain engine operation. Hence, the total idling emissions and cruise emissions are significantly lower than those of other driving modes. CO emission in idling mode for 1000 cc motorcycles was 2.6% of total emissions, though it was 1.8% for 600 cc. HC and NO_X emissions for 1000 cc were significantly higher (12 and 7.5%, respectively) as compared to 600 cc (3 and 2.88%, respectively).

5.3 Observed Emission in Acceleration

In the acceleration process, the engine needs more fuel power to generate enough power to accelerate. The higher the acceleration rate, the more fuel is needed, therefore fuel consumption increases. It can be seen from Table 5 that total emissions of CO, HC and NO_X for 1000 cc are 42, 38 and 39.16%, respectively, while total emissions for 600 cc are 35, 40 and 32%, respectively. The emissions of CO and NO_X for 600 cc were found to be lower in acceleration modes.

5.4 Comparison of Observed Emission Between Different Driving Modes

The EMDC characteristic has a higher percentage of time spent in deceleration than any other driving modes. This was reflected in the emissions: for example, for 1000 cc total CO emissions were found to increase in deceleration modes. Total observed emissions of CO in deceleration modes were 7% more than acceleration, which is also true for HC. This was also 47% more than in cruise and idling modes. For smaller engines of 600 cc, CO emission in deceleration modes was found to be 26% more than acceleration modes. For the engine of 600 cc engines, total HC emission in deceleration modes was found to be 10% more than acceleration modes, while total HC emission in idling and cruise modes for the larger engine size of 1000 cc was more than the 600 cc engines, demonstrating the effect of engine size on emissions. For 1000 cc engines, total NO_X emission in deceleration modes was found to be 8% more than acceleration, whereas it was 40% more than cruise and idling modes. For 600 cc engines, NO_X emission in deceleration modes was found to be 23% higher than acceleration modes. Emissions in deceleration mode were found to be 40-50% higher than cruising and idling modes.

6 Effects of Driving Modes on Emissions

Considerable emissions were observed in acceleration and deceleration modes (accounting for more than 93% of the total emissions where the average speed run along the test route in city centre was 23 km/h). The relationship between total emissions and percentage of time spent in different vehicle operating modes shows polynomial equations. Total CO (g/s) decreases with the increase in the time spent in deceleration increases as time spent in acceleration and idling increases. In cruising mode, CO emissions increases percentage time spent Time spent in decelerations varies in the test run between 47 and 53%; overall time spent in accelerations varies between 39 and 44%, whereas time spent in idling activity varied from 1 to 4.5%.

For HC (g/s) emissions decrease with the increase in time spent in deceleration, whereas it increases in acceleration and idling. HC (g/s) first increases in cruising, then decreases with time spent in cruising mode. In contrast to the earlier, NO_X emissions increase with time spent in deceleration and cruising, whereas it decreases with time spent in acceleration, while NO_X (g/s) initially decreases, then starts to increase after a certain time interval. Standard deviation (SD) of CO emissions varies from 3 to 0.5 for different operating modes, whereas SD ranged from 0.06 to 1.93 in different operating modes. For NO_X, it was 0.001-1.931. This shows that CO emission is more sensitive to vehicle operating modes and had a larger range of standard deviation than HC and NO_X. This approach is very important and relevant, especially to the driving cycle. However, the results should be treated with care as they were obtained from a very limited number of runs. It is strongly recommended to carry out further research with a much larger dataset to verify these models.

7 Modelling Emissions Based on the Time Spent in Driving Modes

Evaluation of the percentage of time each driver spent in each driving event or 'mode' was done by classifying the data from the different test runs into acceleration, deceleration, idling and cruising modes. These data, while not necessarily directly correlated to exhaust emissions in motorcycle for reasons of transient operation, are nevertheless useful for understanding urban driving patterns. Fractions of the time spent in each operating mode and the average emission factors were calculated. The following relationships were found between total emission based on time in seconds and percentage time spent for driving model. The emission models as well as the respective R^2 values for CO, HC and NO_X (all g/s) are developed as shown in Table 6. Although R^2 values are not great, the approach clearly presents a potential directive for the

Table 6 Modal emissions in different driving modes

Pollutant total emission	Driving modes	Model	R^2	Application range (%)
CO (g/s)	Deceleration mode	$-0.0833 * T_d^2 + 7.2177 * T_d - 142.45$	0.2999	47.5-52.8
	Acceleration	$0.483 * T_a^2 - 38.84 * T_a + 788.07$	0.3855	39.5-43.5
	Idling	$0.233 * T_i^2 - 0.899 * T_i + 1.07$	0.8638	1-4.5
	Cruising	$0.0975 * T_c^2 - 0.7844 * T_c + 2.3186$	0.67	4-7
HC (g/s)	Deceleration mode	$0.0069 * T_d^2 - 0.701 * T_d + 17.857$	0.7064	45-43
	Acceleration	$0.0025 * T_a^2 - 0.1982 * T_a + 4.0055$	0.6277	39-46
	Idling	$0.0016 * T_i + 2.1137$	0.556	1.2-4.5
	Cruising	$-0.0018 * T_c^3 + 0.0287 * T_c^2 - 0.1463 * T_c + 0.2538$	0.3506	4-7.9
NOX (g/s)	Deceleration mode	$0.0000006 * T_d^2 - 0.0037 * T_d + 0.0577$	0.2544	45-53.5
	Acceleration	$-0.0003 * T_a^2 + 0.0249 * T_a - 0.4742$	0.1257	39.5-46
	Idling	$0.002 * T_i^2 - 0.0175 * T_i$	0.3251	1.2-4.5
	Cruising	$0.0002 * T_c^2 - 0.0021 * T_c + 0.0079$	0.3969	4-7.8

estimation and assessment of emissions and driving cycles. It should be noted here that these equations are calibrated based on pooled data of two motorcycles. It would be possible to develop a strong empirical relationship by including more engine sizes and number of parameters, where T_a is the % time spent in acceleration, T_d is the % time spent in deceleration, T_i is the % time spent in idling, T_c is the % time spent in cruising.

This can be used to assess the vehicle renewal policy of the Edinburgh motorcycle fleet once accurate emission has been estimated. Table 6 presents the modal emissions model and time spent in different driving models. Although the aforementioned models are complex (due to the large number of equations), the approach demonstrated its ability to discriminate the emissions in a satisfactory way through dynamic-related parameters and in particular through time spent in different vehicle operating modes of the driving cycle, such as time spent in idling cruise, acceleration and deceleration. The similar relationship based on the average speed v, the mean of square and cubic speeds (mv^2 and mv^3, where v is speed), the average of the speed *x* acceleration product (*mva*, when positive), idling and total running durations (T_i idle and T_r running), plus the inverse of the cycle distance has been developed by Andre (2009), Rapone (1995, 2005) and Frey et al. (2003) to obtain emission rates.

8 Summary and Conclusion

Real-world onboard emission measurements are used to measure emission factors. It can be argued that modelling individual vehicle fuel consumption and emissions coupled with the modelling of vehicle kinematics on an urban network could result in more reliable evaluations of operational-level project impacts. Results compared to measurements are somewhat disappointing in absence of accurate measurement of fuel. The influence of onboard emissions with speed and the effect of driving modes on emissions were explored. Onboard emissions provide improvement of instantaneous emission measurements to improve quality of emission forecasts according to driving kinematics (i.e. speed and acceleration). To improve the existing instantaneous emission models, some preconditions must be fulfilled: the emission signals should be measured on a 10 Hz basis, because of their frequency content. In addition, the transport dynamics from the engine to the analysers must be compensated by time-varying approaches. A limited number of test vehicles may not reflect the whole traffic fleet, but owing to the constraints of resources and time it was a feasible solution to understand the emission patterns of motorcycles in different driving cycles.

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