The Vehicle Emissions and Performance Monitoring System: Analysis of Tailpipe Emissions and Vehicle Performance

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Abstract

This paper describes tailpipe emissions results generated by the Vehicle Performance and Emissions Monitoring System (VPEMS). VPEMS integrates on-board emissions and vehicle/driver performance measurements with positioning and communications technologies, to transmit a coherent spatio-temporally referenced dataset to a central base station in near real time. These results focus on relationships between tailpipe emissions of CO, CO_2, NO_x and speed and acceleration. Emissions produced by different driving modes are also presented. Results are generally as one would expect, showing variation between vehicle speed, vehicle acceleration and emissions. Data is based upon a test run in central London on urban streets with speeds not exceeding about 65 km/hr. The results presented demonstrate the capabilities of the system. Various issues remain with regard to validation of the data and expansion of the system capability to obtain additional vehicle performance data.

Keywords: on-board emissions monitoring, on-board sensors, GPS, environmental impact, traffic flow, modal emissions

Introduction

This paper reports tailpipe measurement results from on-board vehicle measurements of both tailpipe emissions and vehicle performance. Relationships between emissions of CO, NO_x, and CO_2 are evaluated against vehicle speed, acceleration rates, and elapsed journey time. The objective of this paper is to demonstrate the capability of measuring on-board emissions using a low-cost monitoring device, the Vehicle Performance and Emissions Monitoring System (VPEMS).

Development of the VPEMS is a collaborative effort between the Imperial College Centre for Transport Studies (CTS) and two industrial partners, SIRA Ltd and Saturn Technologies. The key objective of this project is the development of a cost-effective on-board data collection device. VPEMS has two main components: the Mobile Unit (VPEMS-MU) and the Master Control Centre (VPEMS-MCC). The VPEMS-MU is installed on the vehicle to capture real-time second-by-second spatio-temporally referenced vehicle/driver performance and emissions data (both from tailpipe exhaust and in-cabin). Data captured by the VPEMS-MU is then transmitted to VPEMS-MCC via the Global System for Mobile (GSM) technology for storage, analysis and display. Ochieng et al. (2003) provide additional detail on the system design and specification.

The VPEMS could potentially satisfy the needs of a diverse set of users such as academic and government-based research institutions, transport and environmental planners and fleet operators. This is because it has a flexible architecture that allows flexible functionality through a set of modular subsystems. The sub systems include navigation, processor, performance, emissions, human-machine interface (HMI), communication and master control centre. A detailed description of VPEMS high-level architecture can be found in Ochieng et al. (2003).

In this paper, we first provide a short review of emission measurement techniques and associated modelling issues, to provide some context for the objectives of this project and our analysis of the data. We then describe the test route used for data collection, discuss our analysis, and outline further research objectives in this area.

Emissions Measurement and Modelling Issues

Vehicle exhaust emissions can vary by an order of magnitude within the space of a few seconds, with the response frequently non-linear, due to enrichment or enleanment of the air-fuel mixtures. Therefore, second-by-second emissions data provides a better method for the development of models for estimating vehicle emissions. New measurement methods provide the capability for the development of this type of data. On-board emissions measurements by instrumented vehicles are one such method. While still in their infancy, previous work in this area has generally been with relatively expensive systems expressly designed for research purposes. Several studies have examined on-board measurement methods in recent years with a limited number of instrumented vehicles **(e.g. De Vlieger 1997; Cicero-Fernandez et al 1997; Ensfield 2001; Unal et al 2003;)**.

Typical emissions models currently in use are the EMFAC series of models in California developed by the California Air Resources Board (CARB), the EPA MOBILE model used in the rest of the U.S., and the UK DMRB method as described in the *Design Manual for Roads and Bridges* (Highways Agency, 1999). These are all based upon standardized driving cycles based on running vehicles on dynamometers. More recently, a microscopic modal emissions model, the Comprehensive Modal Emissions Model (CMEM), has been developed (Barth et al. 1996, 1997, 1999, 2001; An et al. 1997). This allows evaluation of traffic operational improvements such as ramp metering, signal coordination, and changes in traffic parameters (Stathoupoulos & Noland, 2003). This model is based on second-by-second tailpipe emissions data from 300 vehicles tested under a variety of laboratory driving cycles on a new dynamometer emissions testing protocol. The MEASURE model (Guensler et al. 1998) is also based on different driving cycles developed for modelling purposes. Another modal emissions database is the European MODEM model, although this data was collected in the early 1990's and is unrepresentative of current vehicle fleets.

Dynamometer tests are usually conducted on a dynamometer under laboratory conditions using pre-defined driving cycles. A driving cycle, which is used to represent driving under different conditions, is a combination of the vehicle's operating modes such as idle, steady-state-cruises, accelerations and decelerations and is usually characterized by an overall time-mean speed (TRB 1995; NRC, 2000). For better quantification of emissions, a driving cycle needs to be representative of real-world driving behaviour. Various problems have been identified with existing driving cycles, such as the underestimation of acceleration effects (US EPA, 1995), the underestimation of the time spent in cold transient mode (Venigalla et al. 1995), and the overestimation of the time spent at stop and at cruise between 40 km/h and 56km/h (St. Denis et al, 1994). Therefore, a common concern with the driving cycles is that they may not be sufficiently representative of real-world emissions (Barth et al. 1996, NRC 2000) and also are unable to allow evaluation of the impact of policies that change driving cycles by changing traffic flow dynamics. Subsequently, emissions measurements from dynamometer tests are characteristically non-representative of actual emissions.

To counter criticisms of dynamometer based measurements and to utilize rapidly developing technology improvements, on-board emissions measurement techniques, including VPEMS, are being developed. This offers the benefit of collecting modal second-by-second emissions data under real-world driving conditions. Using on-board emissions measurement, variability in vehicle emissions as a result of variation in vehicle performance, driver behaviour, and road and traffic characteristics can be represented and analyzed with more detail. However, while providing this benefit, problems remain with designing and building low-cost and robust measurement devices, a hurdle that VPEMS overcomes.

A number of recent studies have used on-board emissions devices. The measured species are mainly CO, CO_2, HC, NO_x and O_2. Particulate data has not been routinely collected although a system capable of doing so is presented in Vojtisek-Lom and Allsop (2001). Most studies also collected data from the engine diagnostic and management system (EMDS), which is synchronized with emissions data. None of the studies considered collecting GPS data except Nam et al. (2003). It is worthwhile to note that GPS data is important for analysis of the spatial distribution of emissions on the road network once it is synchronized with emissions and EMDS data. Some of these studies are reviewed below and summarized in Table 1.

Cicero-Fernandez et al. (1997) discussed the effects of road grade and other loads on vehicle exhaust emissions based on second-by-second on-board emissions measurements. For the development of more accurate mobile source emissions inventories, estimation of emission rates on different road grades is very important. This study found that exhaust emissions of HC and CO increased significantly when driving on grades of approximately 3% or higher and speeds between 35 to 55 mph. One of the limitations of this study is that on-board emissions data were collected from one instrumented vehicle in a restricted domain of pre-determined speeds, low accelerations, and grades.

Holmen and Niemeier (1998) characterized the effects of driver variability on real-world vehicle emissions. This study hypothesized that the variability associated with individual driving styles would produce statistically significant differences in measured vehicle exhaust emissions for the same vehicle under similar road conditions on a single route. This study conducted a field study on 24 randomly selected drivers. The results showed significant (95%) variations in CO and NO_x emissions among those 24 drivers. The results also suggested that the intensity of vehicle operation within a given mode explains more variability in emissions among drivers than the modal frequency. For example, the percent time spent accelerating may be less important than the intensity of acceleration events. These type of parameters are measured by the VPEMS device.

Tong et al. (2000) analyzed on-board exhaust emissions, speed and fuel consumption data collected from four different types of instrumented vehicles such as passenger cars, petrol vans, diesel vans and double-decker buses. The results suggested that fuel-based emission factors (g/kg fuel) varied much less than the time- and distance-based emission factors (g/sec and g/km) with instantaneous speed. The results also indicated that the exhaust emissions during transient driving modes such as acceleration and deceleration were significantly higher than the steady-state driving modes such as cruise and idle in terms of g/km and g/sec, except for buses.

Rouphail et al. (2000) investigated the effects of traffic flow on vehicle emissions by evaluating the relationship between vehicle emissions and control delay. This study also evaluated the rate of vehicle emissions during each mode of travel, acceleration, deceleration, cruise and idle. The results found that vehicle exhaust emissions are the highest during acceleration events followed by cruise, deceleration and idle events. Results shown below from our measurements are similar, with some variation between pollutant type.

Frey et al. (2001) demonstrated on-board emissions measurement techniques and collected real-world representative emissions data that can be used to assist in the design and management of traffic facilities, as well as, monitoring, modelling and planning of air quality. One of the key objectives of this study was to understand the variability in emissions from one trip to another for the same vehicle, route and similar traffic conditions. The results suggested that there is substantial variability in emissions from one run to another. This suggests the need for extensive data collection to properly characterize relationships. The study found that the emissions during the acceleration mode are significantly higher than for any other driving mode for all the pollutants measured.

Unal et al. (2003) evaluated the effect of changes in arterial traffic signal timing and coordination with respect to level of service (LOS) and emissions. The study conducted a total of 824 one way runs representing 100 hours and 2020 vehicle miles of travel on two signalized arterials in Cary, North Carolina. Modal analysis of the collected data showed that emissions rates are highest during acceleration followed by cruise, deceleration and idle. One of the key results from this study was that signal coordination improvements yielded measurable improvements in arterial LOS and reductions in emissions.

Nam et al. (2003) illustrated a comparison of real-world and modelled emissions under conditions of variable driver aggressiveness. The results suggested that aggressive driving produced significantly more emissions.

This review illustrates the wide variety of research objectives that can be investigated by on-board emissions monitoring equipment, especially when combined with other instruments. It also illustrates the potential uses of this type of data both for further research and the development of more accurate emissions models. VPEMS integrates travel, vehicle/driver performance and emissions data into a coherent spatially and temporally referenced database. The relevance of the data to a real world situation can then be directly determined through analysis in a Geographical Information System (GIS). Previous studies have also been limited in their scope, due in part to the high costs associated with running numerous instrumented vehicles simultaneously. VPEMS is intended to be a compact and cost effective solution with a system architecture designed to allow numerous mobile units to download data ‘on the fly’ to a master control center. This allows far greater flexibility in terms of experiment design and greater insight into the dynamics of traffic situations involving multiple vehicles.

Data Collection

We are currently capturing real data with test runs of one vehicle fitted with VPEMS. This vehicle is a 1998 Citroen Synergy minivan. Vehicle performance data can be obtained directly from the engine management and diagnostic system (EMDS). To do so requires an interface with the standard Controller Area Network (CAN) serial bus used by the vehicle systems to communicate with one another. However, the codes used to transmit data on the CAN bus are proprietary and not standardized in Europe. As an alternative, a number of electromechanical sensors are fitted throughout the vehicle to record various vehicle performance data. A diesel powered Ford Focus, for which we have received information on the EMDS data formats, has recently been fitted with a VPEMS device allowing a CAN interface to extract engine performance data.

A GPS receiver currently records the navigation data. Research is on going to integrate GPS with Dead Reckoning (DR) and Map Matching (MM) to obtain better navigation data (Quddus et al., 2003). Two types of instruments are currently used to measure both emissions and in-cabin air quality. This is the iRidium 5-gas analyzer (2 units) and the other is a spectrograph (1 unit). One iRidium analyzer is used to monitor in-cabin air quality at intervals of about every 2-3 seconds while the second iRidium analyzer is used to monitor exhaust emissions at one second intervals. The spectrograph is used to monitor in-cabin air quality at 5 second intervals. The measured pollutants include CO, CO_2, HC, NO_x and O_2 with each iRidium bench and CO, CO_2 and HC with the spectrograph. In the future VPEMS will also contain a particulate sensor based on optical obscuration from particulates in the exhaust flow that will provide a measure of total particulates at one second intervals.

The vehicle fitted with VPEMS can record navigation data (time, location, speed, direction of travel), spatio-temporal referenced vehicle/driver performance data (clutch & brake pedal presses, accelerator position (%), engine speed, fuel flow, vehicle speed) and emissions data (exhaust emissions and in-cabin/ambient air quality). The data collected for the experiment presented here included tailpipe emissions (CO, NO_x, and CO_2 only) and GPS navigational data.

The test route used to collect the data presented in this paper is shown in Figure 1. It forms a 5.52km (3.45mi) loop running through Hyde Park from the Imperial College campus at South Kensington, up to Marble Arch and then back down to the campus. The data set includes maneuvering in the car park at each end of the trip, three sections of signalized urban streets, the run through the park (featuring six raised pedestrian crossings/speed bumps in each direction) and an open avenue with little traffic or obstruction. Driving speeds on this route are generally quite moderate, not exceeding about 65 km/hr. The test was conducted late morning. The weather was overcast but dry, with a temperature of around 23˚C.

Results

The emissions measurements presented here may be affected by a number of error sources relating to the sampling apparatus as currently installed in the prototype vehicle. In these tests, the gas sample is extracted via a t-fitting in the side of the tailpipe after the catalytic converter. This is assumed to be representative of the exhaust in general. The sample is then filtered and dried in several stages before entering the IRidium bench. During this process, reactions will continue to occur in the sample gas (particularly for NO_x and HC). Moreover, in this prototype system parts of the apparatus are linked by silicone tubing, which although chemically inert, may retard or retain the HC fractions in the sample. For these reasons, data for the HC emissions are not presented here. The time for the sample to travel through the system will also introduce an offset. This is currently accounted for by a constant value that may not be appropriate for all conditions. Further work, not presented here is analyzing these error sources as part of the validation process for the VPEMS device.

Results are displayed graphically in the figures that follow. We focus on examining the changes in emissions over time (since vehicle start) for the test run, correlations with speed, and correlations with accelerations.

To calculate the speed of the vehicle we use both GPS and wheel revolution measurements. This was done because of some GPS blockages and positioning errors. These will be fixed by using Dead Reckoning and Map Matching as described in Quddus et al. (2003). Wheel revolution measurements provided a comparison with the GPS data. Figure 2 shows that these match quite well and Figure 3 displays the correlations between these measurements.

Figures 4-6 display tailpipe measurements of CO, NO_x and CO_2, expressed as percent of each pollutant. Calculation of pollutants by g/sec will require data on fuel flow, engine speed, and various assumptions on the combustion process. This data is available either from the EMDS via a CAN interface or a commercial off-the-shelf fuel flow meter and engine speed sensor. This paper reports on pollutant concentrations from the tailpipe, before this conversion.

Figure 4 shows reasonable values for the CO emissions. There is a large spike when the engine is turned on due to sub-optimal operating temperatures in the catalytic convertor. Various other spikes correspond to the conditions encountered during the test drive. NO_x emissions are shown in Figure 5 and do not show a major effect at the start of engine operations, although emissions are relatively high for the first 100 seconds of operation. There is one noticeable spike at the 425 second mark which may be due to an acceleration from a stopped position. CO_2 emissions also show variable behavior over time, most likely due to changes in speeds and accelerations.

Figures 7-9 plot emissions results against speed. Average emissions have been distributed against speed bins of 3 km/hr. The range of speeds omits high-speed operations, since the test run did not have speeds exceeding about 65 km/hr, which is fairly representative of speeds in central London. CO emissions show a small upward trend as speeds increase, while CO_2 emissions are generally flat. We would expect both of these to increase above about 60 km/hr. NO_x emissions show an upward spike around the 60 km/hr bin. This is not unexpected as we would expect NO_x emissions to increase rapidly at higher speeds (compared to the other pollutants measured).

Analysis of similar emissions plots versus acceleration levels generally did not show significant correlations for this test run. However, a disaggregation of the data by driving mode (idle, cruise, acceleration, and deceleration) did show expected results. The definition of each driving mode is arbitrary to some extent. For this analysis, zero speed and zero acceleration are taken to indicate idling, positive speed and positive acceleration (>1.0 kmh/sec) are taken to indicate acceleration, positive speed and negative acceleration (<-1.0 kmh/sec) are taken to indicate deceleration and all other cases are considered cruising. Second-by-second emissions data were divided into these four modes and the average emissions for each mode were determined using the above definitions. Initial start conditions were omitted (about the first 30 seconds of vehicle operation). Results are shown in Figures 10-12.

For CO emissions (Figure 10), average emissions are highest during acceleration modes and lowest during idling. CO_2 emissions (Figure 11) show less variation between the various modes, but are lowest during idling. NO_x emissions (Figure 12) show the highest level during accelerations and very low levels during idling. These patterns are generally what we would expect, although if the data contained more hard accelerations and higher speeds we might see additional variation.

Conclusions and Future Research

The results presented in this paper are derived from the VPEMS device as fitted in our first test vehicle. The objective of this analysis was to demonstrate the ability of a low cost on-board emissions monitoring device to track vehicle emissions in real-time. Our results are consistent with other work that consistently demonstrates the increase in emissions associated with acceleration events and the variation in emissions with instantaneous speed. The VPEMS device also measured emissions spikes during initial engine start conditions due to sub-optimal performance of the emission control system.

The key conclusion of this analysis is to demonstrate the capabilities of low cost emissions sensors that can be integrated with vehicle tracking technologies and engine and vehicle performance data. This opens up substantial future research opportunities by enabling larger scale deployments of emissions monitors (and in-cabin air quality sensors). Future work will include the deployment of sensors on additional vehicles, measurement of particulates, and correlation of emissions effects with traffic conditions. Better characterization of emissions inventories by accounting for modal emissions effects is an additional goal that can be achieved by deployment of on-board emissions devices.

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Table 1: Summaries of studies based on near real-time on-board emissions measurement

Author (s), year	Instrument/ Technique for emissions measurement	Type of emissions data collected	Type of other data collected	Vehicles/type
Cicero-Fernadez et al. (1997)	MPSI Model-9000/Infrared spectroscopy and electrochemical cell	CO, HC and O_2	**EMDS:** Manifold absolute pressure, throttle position, engine speed, coolant temp, manifold temp, vehicle speed **Roadway characteristics**: road grade	1/LDV
Holmen and Niemeier (1998)	OTC 5-gas monitor	CO, CO_2, HC and NO_x	**EMDS:** Engine speed, vehicle speed	1/LDV
Tong et al. (2000)	Flux-2000/NDIR and Electrochemical transducers	CO, CO_2, HC, NO_x and O_2	**EMDS**: Vehicle speed, fuel consumption	4/car, petrol van, diesel van, bus
Rouphail et al. (2000)	OEM-2100/NDIR	CO, CO_2, HC, NO_x and O_2	**EMDS**: Vehicle speed, engine speed, manifold absolute pressure, intake air temp, coolant temp, intake mass air flow, %wide open throttle, open/closed loop flag, fuel consumption.	4/LDV
Frey et al. (2001)	OEM-2100/ NDIR	CO, CO_2, HC, NO_x and O_2	**EMDS**: Vehicle speed, engine speed, manifold absolute pressure, intake air temp, coolant temp, intake mass air flow, %wide open throttle, open/closed	Several/LDV
Brown et al. (2002)	CEM system gas analysers/NDIR, Magneto-Pneumatic, Chemiluminescence , Heated Flame Ionization	CO, CO_2, THCs, NO_x and O_2	**EMDS:** Operating temperatures, shaft speed and torque, vehicle speed and power	1/HDDV
Unal et al. (2003)	OEM-2100/NDIR	CO, CO_2, HC, NO_x and O_2	**EMDS**: Various engine data Outside temperature and humidity, vehicle information e.g., model year, make, vehicle identification number (VIN), engine size, odometer reading, time at which the vehicle crossed the intersections or entered queues.	8/LDV
Nam et al. (2003)	NDIR analyser and UV analyser	CO, CO_2, HC and NO	**EMDS**: Mass, engine displacement, engine speed, gear, fiction, torque, efficiency **GPS data**: latitude/longitude	1/LDV

Figure 1: Test route in Central London

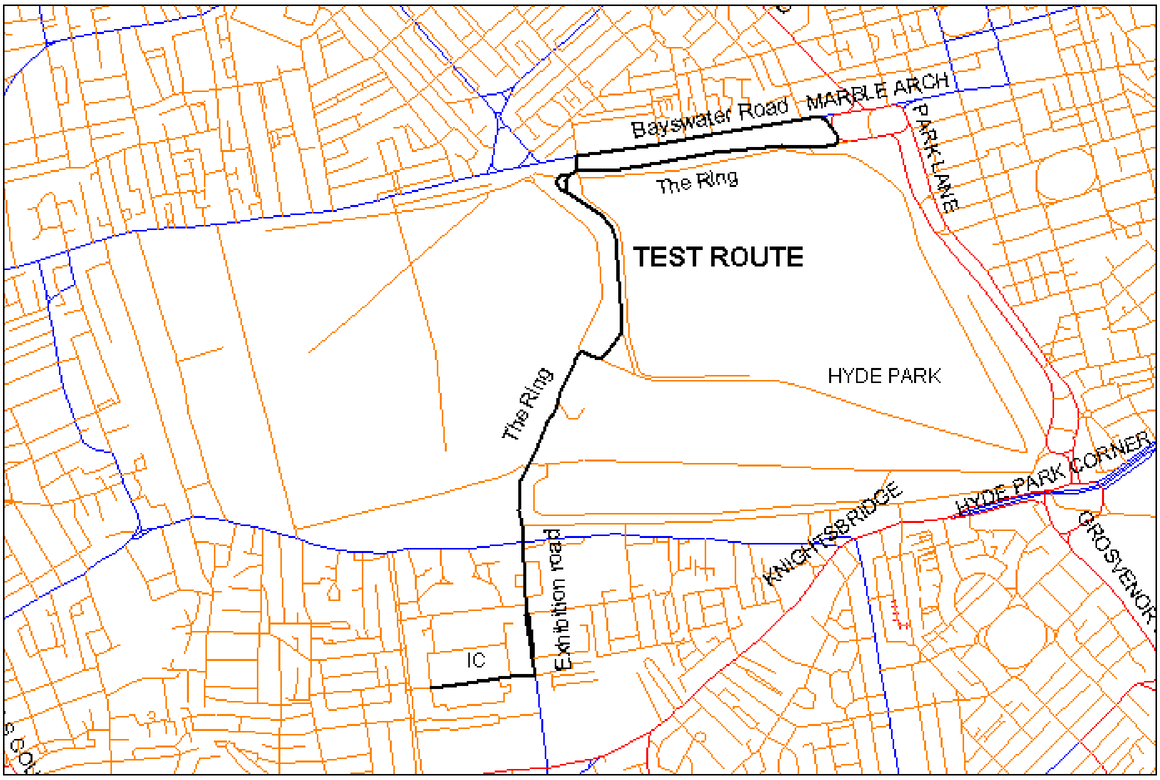

Figure 2: Comparison between GPS speed and wheel sensor measurements

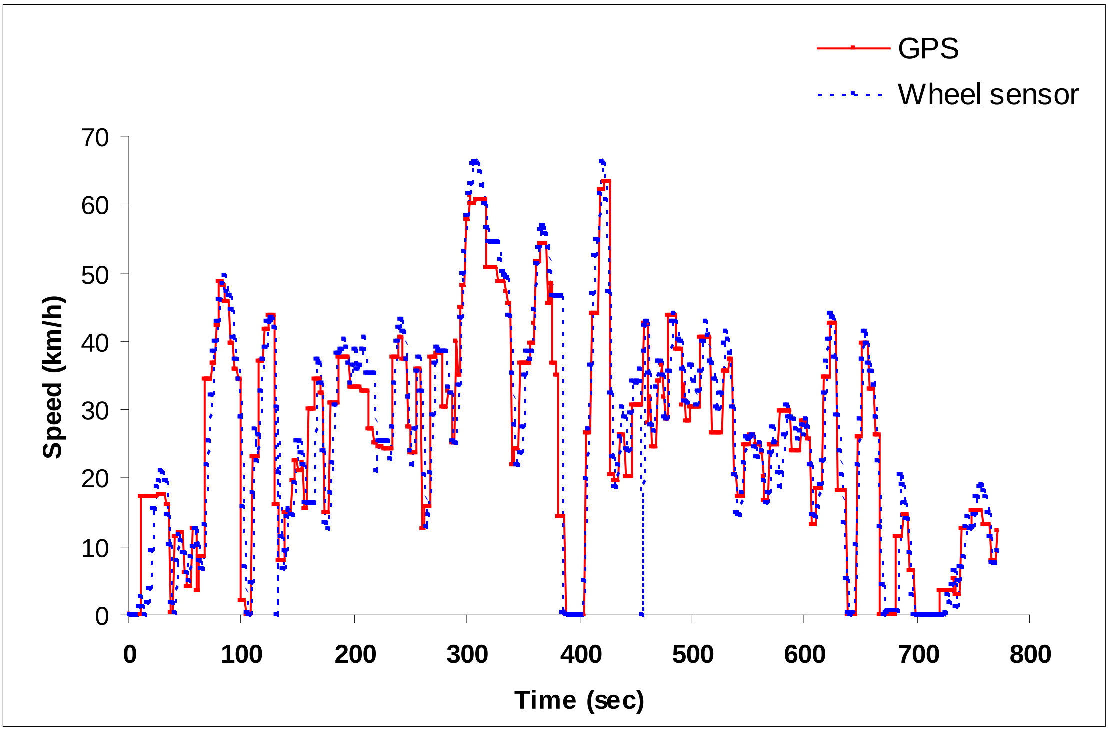

Figure 3: Correlation coefficient between GPS speed and wheel sensor measurements

Figure 4: CO emissions versus time trace

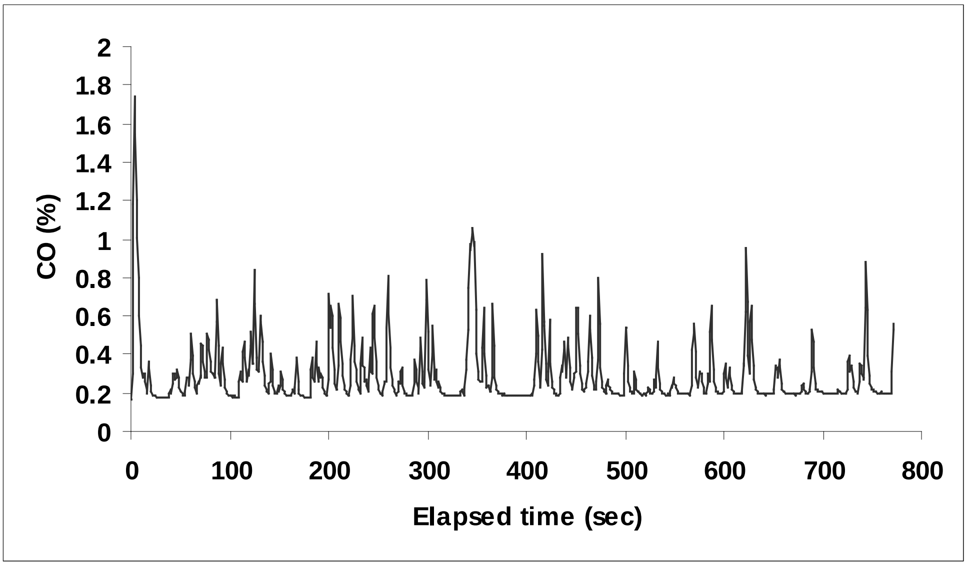

Figure 5: NOx emissions versus time trace

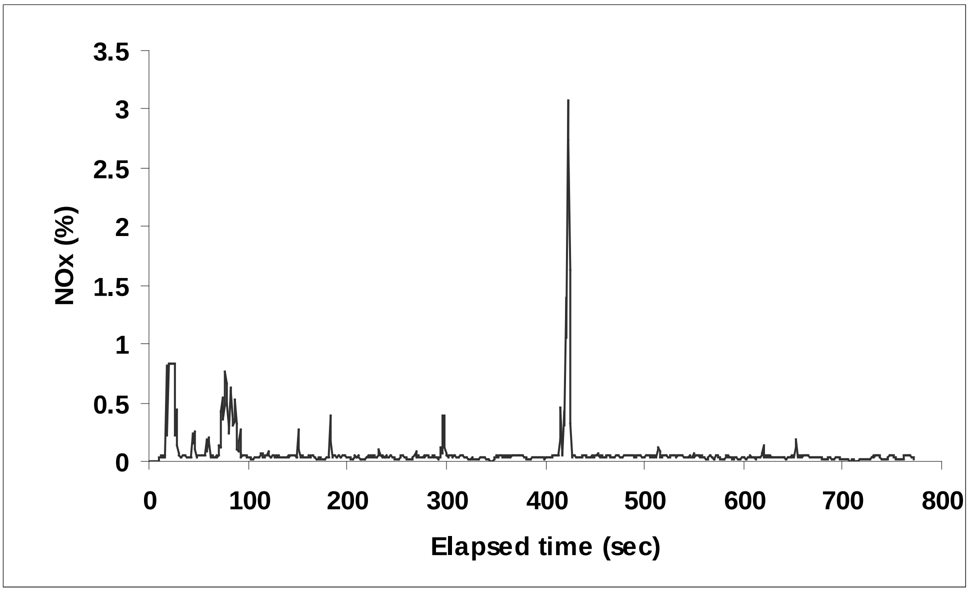

Figure 6: CO_2 emissions versus time trace

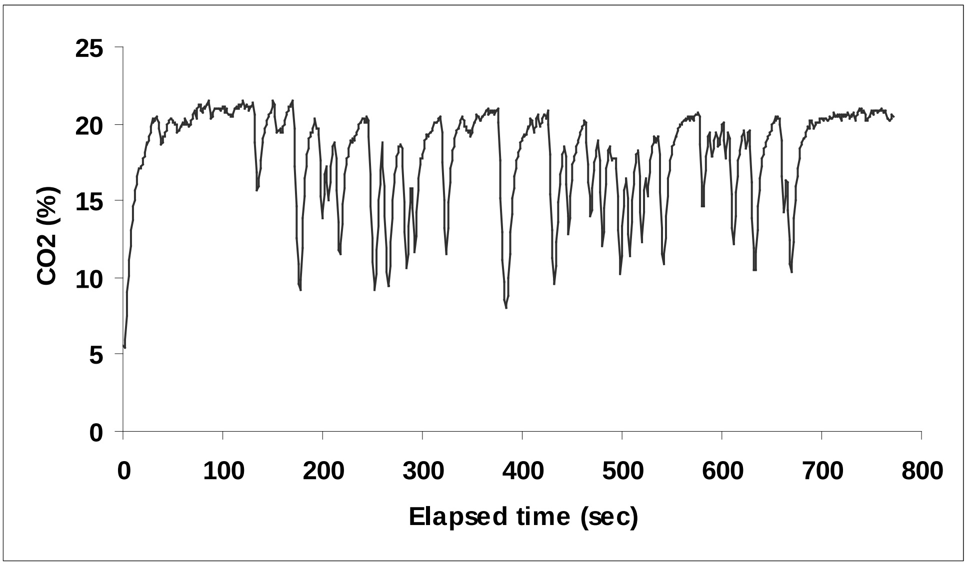

Figure 7: Average CO emissions versus 3 km/hr speed bins

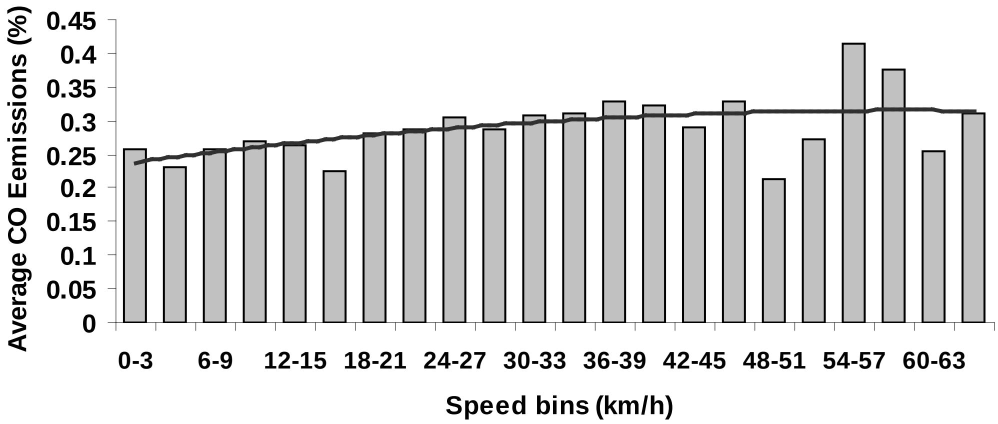

Figure 8: Average CO_2 emissions versus 3 km/hr speed bins

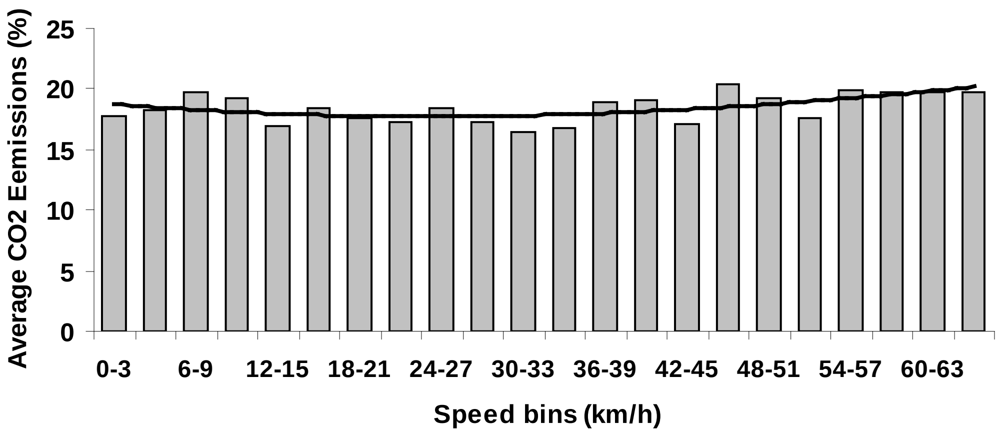

Figure 9: Average NO_x emissions versus 3 km/hr speed bins

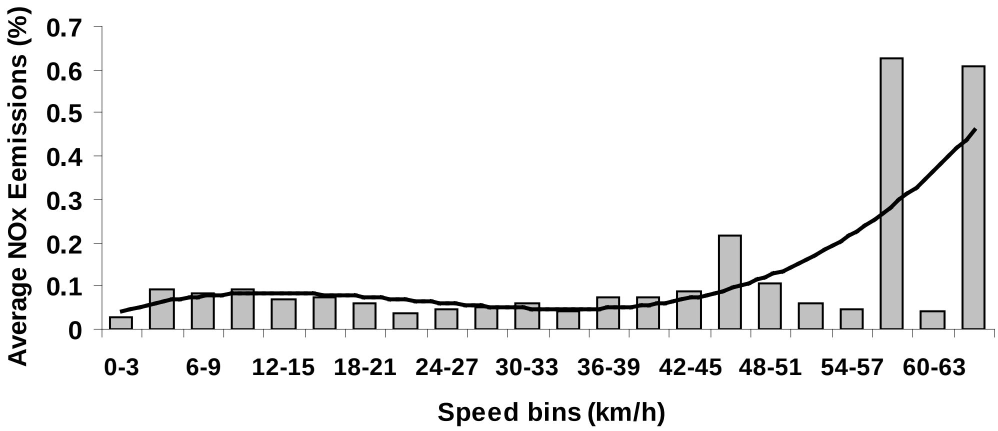

Figure 10: CO emissions by different driving modes

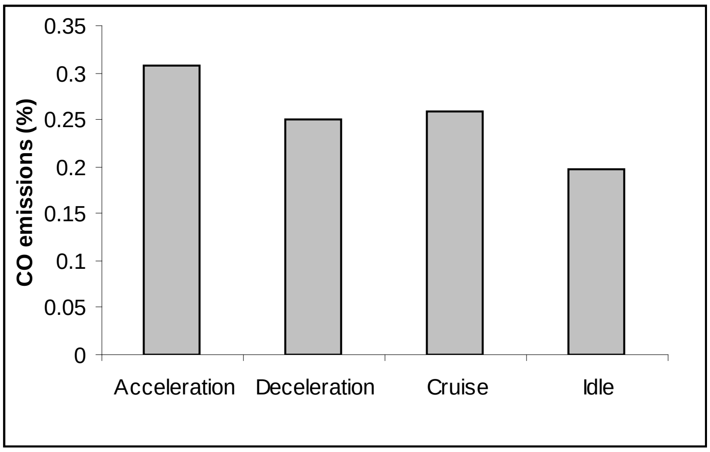

Figure 11: CO_2 emissions by different driving modes

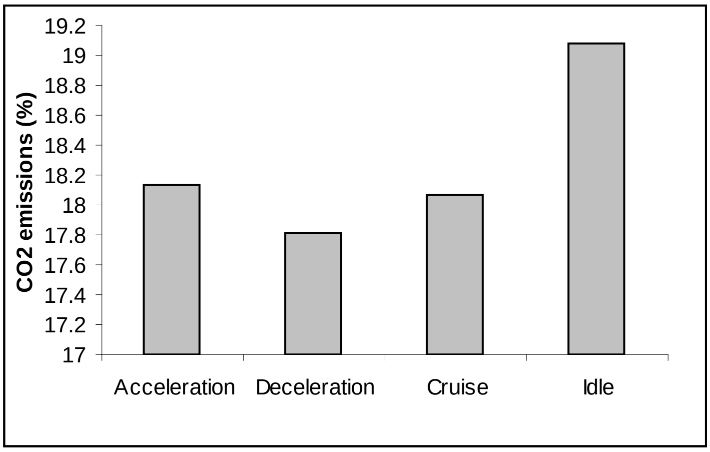

Figure 12: NO_x emissions by different driving modes