Using GPS to estimate emissions and fuel consumption

by Philip Goyns, Department of Geography, Environmental Management and Energy Studies, University of Johannesburg

Vehicle emissions and fuel consumption are of concern, particularly in urban environments, due to their impacts on air quality, the costs of transport, and the consequent effects on human health, biodiversity and mobility.

This article describes a DPhil research project currently underway at the University of Johannesburg. The purpose of the project is to develop an alternative method to characterise emissions and fuel consumption in the City of Johannesburg. The data collected during the project will also be used to calibrate road network models and to study the relationship between vehicle emissions and congestion.

Background
The objective of the new air quality act in South Africa (National Environment Management: Air Quality Act 2004) is to protect the environment while maintaining economic and social development. One of the requirements of the act is that municipalities are to develop emissions inventories for both stationary and mobile sources of emissions. This research focuses on mobile emissions inventories from private passenger vehicles.

Mobile emissions inventories are typically developed using the product of vehicle activity (kilometres driven) and emissions factors which are dependant on driving conditions. Driving conditions are usually described using kinematics such as average vehicle speed or driving cycles (the variations of vehicle speed with time along a typical route within a city.) The US FTP75 (Federal testing procedure), shown in Fig. 1, is an example of a driving cycle used to characterise emissions in the US.

At present there are no emissions factors based on average speed or driving cycles and corresponding emissions factors defined for South African cities. Studies have been done, however, to compare emissions for the NEDC (new European driving cycle) for different fuels and vehicles in South Africa [1] and to compare South African driving cycles (without emissions factors) to the NEDC [2].

The lack of data required to develop mobile emissions inventories for South African cities has resulted in emissions factors being used from models and databases developed elsewhere, such as COPERT (computer program to estimate emissions from road transport [3]), and the Handbook of emissions factors [4]. These models are calibrated for the driving conditions experienced in the countries in which they were developed. The driving conditions in South Africa may vary from these conditions due to differences in road infrastructure, geographical topology, vehicle fleet, and driving styles. There are also limitations in estimating emissions and fuel consumption using average vehicle speed and driving cycles, which will be discussed as part of the description of the emissions model.

Method
Overall approach
The following approach is being used in this project:

Develop a generic emissions and fuel consumption model, which can be used for a variety of driving conditions and vehicle types;

Record vehicle speed, engine operating parameters, and trip routes for vehicles driven within Johannesburg; and

Aggregate the data according to different areas, routes, or even links within the transport system and apply the model to study the impacts of transport activity on the amount of pollutants emitted.

Emissions model
Emissions and fuel consumption are determined by a vehicle’s physical properties, engine operating parameters, emissions controls, and the fuel it uses. Of these factors only engine operating parameters are affected by driving conditions. Average vehicle speed and driving cycles are useful indicators of engine operating parameters.

There are limitations, however, in using these when estimating emissions and fuel consumption as they only regard the forward motion of a vehicle. In reality there are other demands imposed on an engine which impact on emissions and fuel consumption including varying atmospheric conditions, changes in road gradient, and the use of auxiliary equipment, such as air conditioners and heaters.

In order to account for all of the demands on an engine the engine

Fig. 1: The US FTP75 driving cycle.
speed and engine load can be measured directly and used as an improvement to estimates based on average vehicle speed and driving cycles. (Engine load is defined here as the mean effective pressure or engine torque divided by engine capacity.)

The purpose of this model is thus to characterise emissions and fuel consumption for a set of engine speed and engine load patterns. Engine operating patterns were calculated using the results of the EMPA (Swiss Federal Laboratories for Materials testing and Research) emissions measurement program [5-7].

During this program a number of vehicles were tested for several standardised and real-world driving cycles developed at the EMPA. The transformation of driving cycles to engine operating patterns uses the mass, aerodynamic drag, frontal area, gear ratios and engine dimensions along with the kinematics of the driving cycles to calculate the engine speed and engine load patterns for the vehicles tested.

A large number of operating patterns are produced from the source data using this procedure. These are reduced to a set of base patterns for each combination of fuel and emissions regulation by matching similar patterns and aggregating their emissions and fuel consumption factors.

The engine operating patterns can be described using matrices of engine speed and engine load intervals and the percentage of time spent in each interval pair. Fig. 2 shows an example of an engine operating pattern and Fig. 3 shows the set of engine operating patterns calculated for Euro-0 petrol vehicles.

Similar sets of engine operating patterns were calculated for Euro-2, and Euro-3 regulation petrol vehicles and Euro-2 regulation diesel vehicles.

In order to determine the emissions factor for a new engine operating pattern, such as those being measured in Johannesburg, an interpolation procedure is used to match the new pattern as closely as possible to a linear combination of any three of the base engine patterns. Fig. 4 shows an illustrative example.

The emissions rates for the new operating pattern are determined by adding the emissions factors from the base patterns in the same proportions as the linear combination of the operating patterns that make up the new pattern.

The model provides an emissions rate in grams per second of CO, CO\textsubscript{2}, NO\textsubscript{x}, HC, and Fuel consumption for Euro-0, Euro-2, and Euro-3 petrol vehicles and Euro-2 diesel vehicles for a given engine operating pattern.

**Measuring engine operating patterns**

**Equipment**

Engine operating parameters can be measured during real world driving using the sensors built into modern vehicles’ engine control unit using onboard diagnostics (OBDII.) OBDII is the second version of the international standard (ISO and SAE) for onboard diagnostics used in light duty vehicles.

A GPS and OBD data logger are used in combination with the OBD data logger so that the engine operating parameters can be correlated to the vehicle position at any time during a trip.

The equipment used is similar to that described by Barlow and Green (2002) and consists of four sets of: DriveRightCarChip E/X OBDII data logger; FastTrax GPS module; and DGPS-XM4-ALT GPS data logger.

**Experimental procedure**

A randomly selected group of car owners had a set of equipment installed in their own vehicles for a period of approximately two weeks each. The only requirement was that the OBDII socket in their vehicles was operational. (Cars in South Africa are not required to have OBDII implemented yet, but many vehicles sold after 2000 have a working OBD socket.)

No special instructions were given to the drivers in order to avoid changes in driving behaviour. In some cases, however, it was necessary to ask the drivers to plug the GPS unit into and out of the cigarette lighter power socket at the beginning and end of trips as the power socket of some vehicles remained on when the ignition was off. This caused the battery in the GPS data logger to go flat. The equipment required no other human interaction.

The GPS logger logged position and time at one second intervals. The OBD logger logged time and speed at one second intervals and engine speed, engine load, throttle setting, airflow rate, and air temperature at five second intervals. The OBD data logger also logged trip start and stop times (defined by when the ignition is turned on and off respectively) and trip distances.
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**Initial results**

The data collected during this project effectively serves as a travel and engine operation diary for the vehicles being monitored. The data is useful for both emissions modelling and for traffic monitoring and planning purposes.

The different aspects of road transport can be considered using the same data by grouping the location of vehicle and engine activity data according to different criteria: by road type for road capacity planning; by route to consider the impacts of traffic management changes on emissions and fuel consumption along the route; or by grid for emissions dispersion models.

The data presented here was collected between April 2006 and Jan 2007 from 14 vehicles and 1264 trips. Approximately 16 000 km were driven in 330 hours at an average speed of 48 km/h. Fig. 5 shows the roads and road types that have been travelled during this project.

The difference in driving conditions for different road types and time of day has been considered by looking at the speed distribution for three road type groups: freeways; main roads; and residential streets. Figs. 6 and 7 show the differences in driving conditions for the morning commute and the period after the morning commute using vehicle speed profiles.

The congestion on the freeways in the morning commute is evident from the absence of speeds approaching the speed limit. There is also a considerable amount of time spent standing still or moving slowly (0 - 5 km/h interval) for both freeways and main roads during this period.

The 09h00 to 12h00 time period shows both an increase in average speeds for freeways and main roads and a reduction in the time spent in the 0 - 5 km/h speed interval.

The streets show little differences between the two time periods. As a first approximation to the emissions estimate, aggregate engine operating patterns are calculated for the different road types and time of day. Data from one vehicle is used to demonstrate the impact of driving conditions on engine operating parameters.

Figs. 8 and 9 represent freeway engine operating patterns. Fig. 8 is for morning trips and Fig. 9 is for midday trips.

There is a clear difference between the patterns in Fig. 8 and Fig. 9. In Fig. 8 there is approximately twice as much time is spent idling as there is in Fig. 9. There is also a larger range of engine speeds which would indicate more frequent gear changes and acceleration cycles as experienced in congestion. In Fig. 9 more time is spent in higher engine speeds and higher loads.

Figs. 10 and 11 represent main road engine operating patterns. These operating patterns are similar to each other but, as with the patterns from freeway driving, more time is spent idling during the morning rush hour than later in the day.

Emissions factors have not been calculated for the different road types yet as data are still being collected.

The next step in the process is to disaggregate the data further to gain more details about the severity of pollution by location. The ideal case is to be able to calculate the rate of emissions from transport for any square on a grid of 1 x 1 km over the city.

This can be done by calculating an average engine operating pattern for each square of the grid for different periods of the day and calculating the emissions and fuel consumption factors for the pattern. The procedure of disaggregating the data into a grid is in the process of being developed. Ultimately a family of grids is sought, each representing a different layer of interest. For the purposes of this research the following layers are needed: speed, emissions model. It also provides a proof of concept of a method for capturing the emissions and fuel consumption from transport for any square on a grid of 1 x 1 km over the city.

Average speeds from all the trips between 06h30 and 09h00 have been aggregated for a grid over the City in Fig. 12 to illustrate the format of the desired results.

From Fig. 12, and with the help of some of the road details from Fig. 5, it can be seen that congestion is worst at the access points to the freeways and in the Sandton area. Congestion along the M1 and N1 is also evident from the low average speeds for freeways.

The data represented in Fig. 12 along with an equivalent grid of traffic counts can be used to develop speed flow relationships which are used to optimise traffic flows and to calibrate the road network models used by the City of Johannesburg.

### Conclusions and further work

GPS and OBD are effective in helping to estimate emissions and fuel consumption from road transport and identifying the location of where emissions are most severe. Vehicle speed and location also provide useful information regarding vehicle activity within the road network and in finding congestion hotspots.

This research has helped to develop an emissions model. It also provides a proof of concept of a method for capturing data needed to calculate emissions, fuel consumption and transport activity.
The methods developed and used in this research provide a means to do a before and after measurement of changes in emissions and fuel consumption due to changes in road infrastructure and traffic management measures. Some examples of where this may be useful are in assessing the impact of dedicated bus and high occupancy lanes, and the consequent emissions from the other vehicles affected by such implementations.

During this project data has been collected and assembled manually using only four sets of equipment. This process is time consuming and only allows one to collect data from four vehicles at a time.

The method of collecting data can be developed further by using telemetry and a centralised database to automate the process. In this way a fleet of vehicles can be monitored continuously. This will not only allow emissions to be modelled in more detail but will also provide an instantaneous traffic monitoring tool.

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References


Contact Philip Goyns, Department of Geography, Environmental Management and Energy Studies, University of Johannesburg, philip@goyns.com