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Modelling urban bus transport emissions in Santiago de Cuba

By Dr James P Warren and M Sc. Jordi Mirabent Ávila

Abstract—This study described and focuses on the public transport bus system in Santiago de Cuba. Specifically we explore the fuel consumption of the various diesel buses over a three year period from 2007 to 2009 and with a forecast for the forthcoming years.

The study considers the potential for fuel savings through a variety of methods which are each described and then modelled. Pollution is also calculated for a variety of scenarios and some suggestions are made in order to lower the overall emissions of the fleet.

Key Words—Santiago, buses, transport, emissions.

I. INTRODUCTION

This paper presents in English, for the first time, to the authors' knowledge, a fairly comprehensive overview of the bus system operations and emissions in the city of Santiago. The aims of the paper are to document the trip characteristics, vehicle usages and calculate a reasonable inventory of emissions from the bus system over a continuous three year period. The paper also attempts to forecast future emissions under limited scenarios and each of these is explained in more detail.

In this introductory section a short explanation of the general geographic and local characteristics is presented. The section also describes how many buses there are in Santiago, the arrangement of public transport service along with some of the general characteristics which readers unfamiliar with transport in Cuba may find useful. The paper continues on to the Methodology section which explains how the various input data was

decomposed to yield more meaningful outputs. These outputs are then further explained in the combined results and analysis section, and the final summary points are given in the conclusions.

Santiago de Cuba: region and city

This section, which gives an overview of the region and city is adapted from information extracted from Annual Statistics for the region (ONE, 2009a). Santiago is the second largest city of Cuba, after Havana, situated in the south of the eastern region in the province of the same name. The province is bounded in the south by the Caribbean Sea. To the north lies the province of Holguin and in the east and west are Guantanamo and Granma province respectively. The region represents just over 9% of Cuba's population with a density of 170 inhabitants per km², comprised of 1, 047, 181 people in the region in 2009.

In the city of Santiago de Cuba, the population is 493, 700 inhabitants with a much higher density than that of the region, calculated at ~ 481 persons/km². The municipality area is ~ 1026 km². In this paper Santiago de Cuba is referred to simply as Santiago, and generally means the area contained within the municipal city boundaries.

Transport motivations and structures

Public transport is achieved in the city limits and beyond by a fleet of buses with a mixture of models and makes. This agrees with Gakenheimer's claim (see below in Table 1, number 4) that a fleet mixture presents difficulties in yielding consistent fuel economies as well as resulting in sometimes adverse driving situations. These can occur

when, for example, animal traction, large and small motor vehicles along with cyclists and pedestrians are found in crowded city traffic situations. However these mixtures it must be remembered achieve levels of daily mobility which are reasonable given the various circumstances (e.g. shortage of supply, parts, etc).

Previously a major case study on transport in Havana (Enoch et al, 2004) considered the thirteen attributes from Gakenheimer's developing country characteristics; some characteristics are indeed valid for Santiago de Cuba. The authors have chosen to focus only on those characteristics which are most relevant to the study presented here and thus this table contains only the seven characteristics which seemed most appropriate to this city situation.

Table 1
Transport characteristics in developing countries: the case of Santiago de Cuba
(column one adapted partly from Gakenheimer, 1999)

Characteristics	Comments for Santiago
1. Travel demand far exceeds the supply of facilities, particularly road space	True, although it is the supply of public transport rather than road capacity that is the critical variable.
2. High share of trips by public transport	True. Low carbon modes (walking, cycling) are used extensively.
3. Greater differences in vehicle performance	Wide variety of vehicle types with many developed as a direct response to the Blockade.
4. Inadequate street and highway maintenance	True in certain areas due to the situation and lack of resources such as road tar, and other street furniture.
5. Fewer legal constraints on the use of new technologies	True. Mobility is facilitated by all modes.
6. Weak driver discipline	Possibly true, although traffic laws are rigidly enforced and there are many police. In some cases tourist drivers have been observed driving without due caution.
7. Capital is scarce and operating subsidies difficult to sustain	A lack of hard currency is a major problem and causes a relatively low use of the total vehicle fleet due to shortages.

Concerning number 2 and the high uptake of public transport to achieve mobility, the authors estimate that approximately 70-85% of all motorised trips are met by the bus system. This agrees somewhat with previous work in Havana, whereby buses carried some 27-34% of all passenger trips (see Table 2, Enoch, et al, 2004). This estimate is difficult to calculate as there has not been a wide trip purpose survey for some time in Santiago but nevertheless, bus patronage is believed to be high and significant share.

Buses, in this study, are categorised into four major route segments namely urban, sub-urban, inter-urban and other. Generally urban buses cover the dense urban area, approximately 5-8 km in distance, whilst sub-urban buses begin to reach the other towns just beyond the municipal city boundary. The interurban services could also be called intercity as they reach usually far beyond the

city boundaries to other cities and municipalities. Similarly to Havana city centre these are sometimes called satellite or dormitory services as they serve the outlying towns with a main motivation for travel being a commute to the workplace. Other buses include rural services, and charter services; rural provides for those travelling to the outlying villages and towns. Charter services are buses which are contracted out for travel sometimes by employers, or others based on the contract required which stipulates the departure and arrival points.

Bus makes and models include a wide variety of units, but in general can be characterised into larger articulated units carrying approximately 150-250 people (such as the camello- International/Volvo, or Liaz and Yutong) and also smaller bus units (70-88 people) with models by Daewoo, Yutong, Busscar and Mercedes Benz. Generally speaking the articulated buses are used mainly for urban city services, whereas some older camellos service some of the intermunicipal and interurban services. It is recognised the older camello models have slightly lower levels of comfort and are more susceptible to dangerous road surfaces. The smaller units tend to be used for city services. There are also light and medium trucks (such as the Zil 131, Fiat, etc) used for transport, but these are to a much lesser extent and are not considered in this study.

Compared with other countries Cuba, and this includes Santiago, has very reasonable priced fares with typical ticket prices of 20 cents for most journeys. Longer trips to satellite towns cost a still reasonable 1, 2 and 5 pesos. Speed is also reasonable being about 40 kph in the city, and perhaps 60 kph in the periphery with slightly lower speeds in rural areas, partly due to the specific road conditions.

II. METHODS AND METHODOLOGY

This section will describe the methods used. Raw data was acquired from the public body of transport statistics and has been re-calculated to yield various parameters, including total emissions and energy consumed for the entire fleet. Input values consisted of total fuel consumed, total trips achieved, total passengers transported, and number of bus units available for use during that given year.

Other reported units included measured occupancies, fuel consumptions and some limited mileage readings based on the route types used in the city. These are namely: urban, sub-urban, inter-urban, rural and charter routes.

In this study, all fuel consumed was diesel grade, 0.83 kg/litre, for all of the buses studied. Typically there are approximately 190-250 bus units stabled at any given time, but on daily basis the availability is approximately half of the entire fleet. The available units utilised for carrying passengers was used in order to derive occupancies and other parameters. For instance in 2007-2009 the overall units modelled was 63-69 buses per year. Each litre of fuel combusted produces 2.63 kg CO₂.

Bus types, by make, model and engine type, were available but not linked directly to route types as described above. In general where a specific fuel consumption is not known, by recording, it was assumed to be 2.46 km driven per litre fuel consumption. This agrees well with results by Borken et al (2007) where that study uses fuel consumptions of 2.44-2.53 (for Africa) and 2.38-2.46 (for Latin American countries), with all units in km per litre (see Table 4, bus & coach, diesel fuelled, page 6). These values in general also agree well with those for fuel consumption by Diaz (1998) which shows that approximately 67% of all diesel fuel is used by the heavy duty diesel sector of vehicles.

To estimate the total emissions for each bus type the authors have used a type of decomposition formula (called ASIF after Schipper, et al, 2009) and described here as “Broadly speaking, emissions (G) in the transport sector are dependent on the level of travel activity (A) in passenger km (or ton-km for freight), across all modes; the mode structure (S); the fuel intensity of each mode (I), in liters per passenger-km; and the carbon content of the fuel or emission factor (F), in grams of carbon or pollutant per liter of fuel consumed (page 13, section 6.27)”. This study uses the ASIF methodology, holding fuel consumption relatively constant at ~2.46 km/litre as described above for the larger vehicles. Smaller buses achieve ~1.49-1.56 km/litre. Emissions for each pollutant are shown in Table 2 from two sources and the values agree well for heavy diesel engine characteristics.

Table 2
Transport emissions from diesel powered buses (g/km)

Source	CO ₂	CO	HC	NOX	PM
Diaz (1998)	1002-1140	11.49	2.55	13.4	not stated
Borken et al (2008)	958-992	5.1-5.5	2.5-3.0	13.6-13.9	0.89-1.01

In this study the values from Diaz are used along with the value of PM (particulate matter) from Borken as shown in preceding Table 2 for the larger vehicles. Similar values have also been reported by Vasconcellos (2001, Table 14.4). These emission values over distance are checked by converting the total fuel consumed for each bus type into CO₂ emissions and then dividing, where possible, by the recorded overall distances reported for each bus category (see final column Table 3, this paper).

Due to the smaller distances covered and less data for both the charter and the rural bus services, those bus results are not presented in this paper. Other assumptions are explained in the following section.

III. RESULTS AND ANALYSIS

In this section the figures and emissions for Santiago de Cuba under different circumstances for each type of bus are shown as a function of time. The study also attempted to forecast trips, fuel and occupancies into 2010-2012 based on specific growth rates for passengers.

Average trip lengths were found to increase for each type of bus route service as expected, and with those reaching destinations further away being longer. Occupancies, annual distances, annual vehicle miles and emissions are shown in Table 3.

Table 3
Santiago bus system characteristics, averaged for the 3 year period

Mode	typical trip length (km)	occupancy (persons/trip)	annual vehicle distances (km/yr)	Emissions, estimated CO ₂ kg/km
urban	12.2	110.6	81,000	1.50
Sub-urban	19.1	102.8	107,700	0.99
Interurban	25.2	89.5	71,400	1.07
Rural	69.1	61.3	~ 26,000 (est.)	nr
Charter	34.1	44.6	nr	nr

(Notes: nr not reported, due to lack of data, est. estimated value).

Data in Table 3 represents the averages of a three year period from 2007-2009 inclusive.

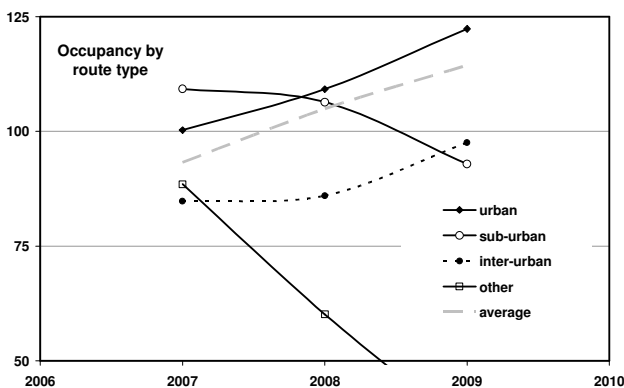


Fig. 1: Occupancy by route type as a function of time for the various bus types, with average values given in grey dashed lines.

Figure 1 demonstrates the relatively high levels of occupancy achieved in this extended city bus system and the annual changes. These changes tend to occur due to shifting bus makes and models from one mode to another to meet demand. As noted in Iles (2005, p 251): “In addition to a mixed fleet in terms of make, model, type and age profile, a common problem in developing countries is that fleets are in poor condition, with an excessive number of vehicles out of service at any time, usually awaiting repair. Often many of these are beyond economic repair...”. This is not always the case here, but certainly many of the factors that are noted are probably involved to some extent.

The overall annual miles per bus are high and as with occupancy vary from year to year. It is clear that these relatively high loads, along with the terrain of the city and surrounds (as noted by Schweid, 2004) can be detrimental to the vehicles and demands very robust buses.

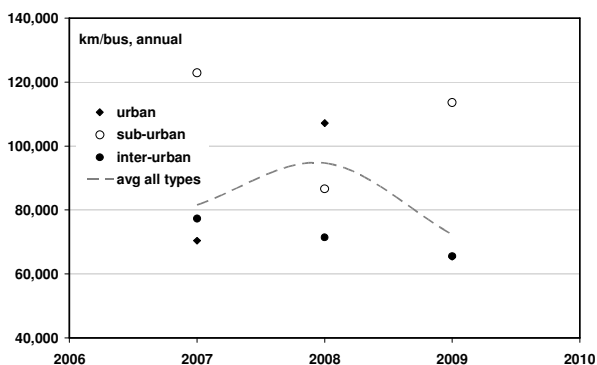


Fig. 2: Annual distances per bus type for a range of buses over 3 years.

Average annual distances for all service (see dashed line in Figure 2) show that a range of

72-95,000 km per bus is achieved each year. The various bus types, with average values given in grey dashed lines (with no symbols) shows that there are indeed very high mileages each year.

Table 4
Transport bus system characteristics in Santiago based on ASIF matrix (2009)

Mode	A		S		I		F	
	travel km/yr	share of bus km % (*)	fuel used (litres)	efficiency (km/litre)	CO ₂ (tonnes)			
urban	3,269,196	66	2,134,846	~1.53	5,615			
sub-urban	795,520	16	299,938	~2.65	789			
interurban	524,617	11	213,259	~2.46	561			

(Notes: * refers to share of total bus kilometres and excludes two-wheeler, truck, rail, car, and walking/cycling; rural <0.5 %, charter ~8 %).

Table 4 shows the application of the method to the city being studied here. The ASIF methodology (see Table 4) gives results which are in good agreement with converting fuel into emissions directly; for example the urban bus mode reports 5615 tonnes for ASIF, and fuel combustion reports 5620 tonnes. These values are probably due to slight errors in the fuel intensity values and are within the limits of the calculation. It is straightforward to calculate the total tonnes of all the emissions for the bus system, such as those shown in Table 2, but for brevity those results are not shown here.

Previous work (Mirabent Avila & Arias, 2008) has recommended that in general further work with more specialised technologists may help increase the understanding of where the bus system is most efficient terms of energy. They also consider the reduction of mobility which has taken place since the 1988-1989 period, but also how the overall price of fuel has consistently risen. These price increases, although subsidised, clearly affect the supply of fuel and then in turn may affect the overall bus system indicators such as ticket prices, passenger numbers and services provided.

When compared against a small range of cities which also use public transport systems, especially buses, their data (UITP, MCD2, 2006) shows that Hamburg, Munich, Moscow and Sao Paulo all have trip distances of 9, 10, 11 and 12.4 km/trip, respectively. For energy consumption, the whole picture is more difficult to discern but in general terms Santiago has good passenger movement in terms of people carried by energy expended, despite some fuel efficiency issues.

IV. CONCLUSION AND FUTURE WORK

In this section the authors outline some potential ideas and indications about how to make the city cleaner and better in the transport systems. One might want to consider what level of emissions and energy other bus systems give in other countries and with this in mind, Indian buses are achieving ~ 3.76 km/litre, under usual conditions in the year 2000 (Table 2, p 17, Schipper et al), which is significantly better than the values observed here. Other examples include Ha Noi (2005, p 16) 2.08 km/litre and also Japan which achieves 2.95 km/litre (Borken, et al 2008) in the year 2000.

This study has shown that despite various difficulties in the transport system that relatively high levels of fuel efficiency (in terms of passengers carried), occupancies, and annual bus distances covered are high and comparable to other cities with similar characteristics. If availability of bus units can be improved then these extra services will most likely be quickly filled, and this in turn will increase demand on fuel supplies.

It would be useful to model a variety of bus scenarios for the city using the basic work completed here. The scenarios could include a decrease in fuel consumption in order to see what the overall mobility that could be provided using the same level of fuel inputs. Also further comparisons of the city wide system with other cities of a similar population or income level would also be interesting, but the initial considerations against a variety of cities, seems to show that Santiago is performing well. Further work to complete a fuller range of different measures and indicators would also help understand more completely all of the issues surrounding the overall efficiency of the bus system in the city.

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