Positive mean acceleration for the determination of traffic emissions*

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*Trabajo a ser presentado en el Congreso Internacional "Transport and Air Pollution", a efectuarse en Graz, Austria, 19-21 de junio 2002

ABSTRACT
Road transport is the major source of air pollution in urban areas. Therefore, it is necessary to quantify emission levels as accurately as possible, with appropriate spatial and temporal resolution. Estimation of emissions from road vehicles is usually calculated through emission factors dependent of mean speed. This paper discusses the effect of positive mean acceleration when estimating gaseous emissions from passenger cars. The methodology is based in experimental results using five local driving cycles representing traffic conditions in Santiago, Chile. A model to determine positive mean acceleration from urban traffic flow is presented, discussing its relationship with both average speed and road characteristics. Emissions from both catalytic and non-catalytic passenger cars are shown, using average speed and positive mean acceleration as controlling parameters. Nitrogen oxides are highly dependent of acceleration, while carbon monoxide and total unburned hydrocarbons are well correlated with average speed. Positive acceleration values up to 1.7 m/s^2 have been found under urban driving conditions, whereas emission estimation from experimental results is available only until 1.2 m/s^2. The whole effect of including acceleration into an emission inventory for mobile sources in Santiago de Chile is presented. A mesoscale transportation model provides traffic activity and emissions are calculated using a COPERT-based approach. This research is part of a wider project funded by the Transport Planning Commission in Chile (SECTRA).
Key words: emission factors, acceleration, passenger cars, urban transport

1. INTRODUCTION

The modeling of air pollution produced by traffic activity has been widely used to develop emission inventories in urban areas (Zachariadis et al, 1997; Barth et al, 1996). There are different approaches to obtain spatially and temporally disaggregated traffic information, such as surveys (Cardelino, 1998), transport models (Algers et al, 1998) or information on real time (Reynolds et al, 2000). The main limitation of surveys is that they provide information limited to a given instant of time and geographic location, whereas acquisition of information on real time requires a complex adaptive traffic control system. The more extended approach corresponds to traffic models, which can simulate complete urban domains with different levels of spatial and temporal disaggregation. However, they still do not contain all the required information for the compilation of a complete emission inventory (Bull et al, 1997).

Transport sector is a dominant source of urban air pollution, so it is important to quantify their emission levels as accurately as possible. The more accurate the simulation of traffic activity, the better the pollutant emission estimation will be.

Main activity parameters provided by the transport model are the traffic volume and the travel times associated with the sections or arches forming the road system of the urban area under study. Estimation of air pollution emissions is mainly based on these two activity parameters, multiplied by emission factors, which provide the mass of a specific pollutant by distance unit traveled by each type of vehicle. This estimation scheme is based on the bottom-up methodology and it has been used to calculate the emission inventory from mobile sources in the city of Santiago, Chile.

2. MODEL DEVELOPMENT

2.1. Estimation of positive mean acceleration from traffic activity

The use of an acceleration estimation methodology by arch is suggested, which is included in the HDM interurban method version 4 (Modeling Road User Effects in Highway Development and Management Research). Section 6 of said model (Congestion Effects) provides an acceleration model based on a work by Bester (1981), with modifications that improve this original model. Additionally, this study assesses the method's suitability to the urban case, comparing the model's estimations with measurements carried out in networks of the road system of Santiago in floating vehicles ("bubble" method), equipped with instant speed sensors.

Basically, the Bester's original model assumes that a driver's accelerations (positive and negative) follow a normal distribution. The acceleration standard deviation or acceleration "noise" provides an indication of the seriousness of speed shifts. This acceleration noise (σ_a) may be considered to be composed by two elements: the natural acceleration noise (σ_{an}) and the noise induced by traffic (σ_{at}).

$$\sigma_a = \sqrt{\sigma_{an}^2 + \sigma_{at}^2} \qquad (2.1)$$

The Bester's original model proposes the use of a constant value for the natural acceleration noise, which corresponds to 10% of the maximum value of the acceleration total noise. The noise associated with traffic is null for low vehicle flow conditions and starts to increase as a certain Q_0 flow threshold is exceeded.

The HDM-4 model modifications to the work of Bester incorporate vehicle flow as an independent variable instead of traffic density. Furthermore, it is established that the intersection between natural noise and noise associated with traffic is variable and not constant. These modifications result in the following equation:

$$\sigma_a = \sqrt{\sigma_{an}^2 (1 - \sigma_{atrat}^2) + \sigma_{a\max}^2 \sigma_{atrat}^2} \qquad (2.2)$$

where

$$\sigma_{at\max} = \sqrt{\sigma_{a\max}^2 - \sigma_{an}^2} \qquad (2.3)$$

$$\sigma_{atrat} = \frac{\sigma_{at}}{\sigma_{at\max}} = \frac{1.04}{1 + \exp(a_0 + a_1 \cdot RELFLOW)} \qquad (2.4)$$

RELFLOW is the relative flow, a_0 and a_1 are regression coefficients, which are estimated through the equations:

$$RELFLOW = \frac{Q}{Q_{ult}} \tag{2.5}$$

$$a_0 = 4.2 + 23.5\left(\frac{Q_0}{Q_{ult}}\right) \tag{2.6}$$

$$a_1 = -7.3 - 24.1\left(\frac{Q_0}{Q_{ult}}\right)^2 \tag{2.7}$$

Q is the total flow in a road, Q_0 is flow under which traffic intersections are insignificant and Q_{ult} is the road capacity.

This model is valid for light and medium sized vehicles (private transport) in interurban conditions. The case of public transport will not be discussed from the point of view of accelerations because there is no national experimental information that permits to relate speed shifts with emissions. Besides, it is considered much more relevant to improve the quality of the road information assigned for public transport instead of estimating accelerations associated with this probably inaccurate information.

2.2 Adaptation of the HDM-4 model to Santiago urban conditions

With the purpose of verifying the suitability of the method for estimating accelerations in urban conditions, their results have been compared with experimental measurements obtained from networks of the Santiago road system. To this end a database collected in the November-December 1997 period was used within the framework of a study developed for determining driving cycles of light passenger cars (Corvalán et al, 2000).

The experimental information analysis has permitted to establish that the main deficiency of the original model is the acceleration range (0-1 m/s^2). In the urban case, mean accelerations reach maximum values fluctuating between 1.5 and 2.0 m/s^2, for which reason a new range from 0 to 1.7 m/s^2 was defined in the present model. To this end the HDM-4 model original curves were adapted, modifying the 2.4 and 2.7 equations by the following parameters:

$$s_{atrat} = \frac{s_{at}}{s_{at\max}} = \frac{1.04 \cdot 1.634}{1 + \exp(a_0 + a_1 \cdot RELFLOW)} \tag{2.8}$$

$$a_1 = -8.103 - 24.1\left(\frac{Q_0}{Q_{ult}}\right)^2 \tag{2.9}$$

In addition to the above, the field information analysis permitted to verify the validity of the two hypotheses established in the application of this model, which are: (a) the mean acceleration distribution in an arch is Normal and (b) this distribution mean is equal to zero. Thanks to the verificaton of these hypotheses, now it is only necessary to model the positive accelerations and assume that decelerations (or negative accelerations) will follow the same tendency.

The fact that the mean distribution is close to zero means that every modal acceleration event is followed by a deceleration, and that the total effect of positive and negative accelerations results in null average for every arch. However, from the point of view of emissions it is important to know the aggressiveness level of these events since the emission rate is different whether the vehicle is in one mode or the other and this difference increases as these incursions get away from zero.

Applying the corrected equations set described in the previous paragraphs, the positive mean acceleration curves are obtained in function of the total flow in the arch, for each category. The following figure shows a graphic representation of these curves (sections 1-9 are increasingly distributed from left-hand to right-hand):

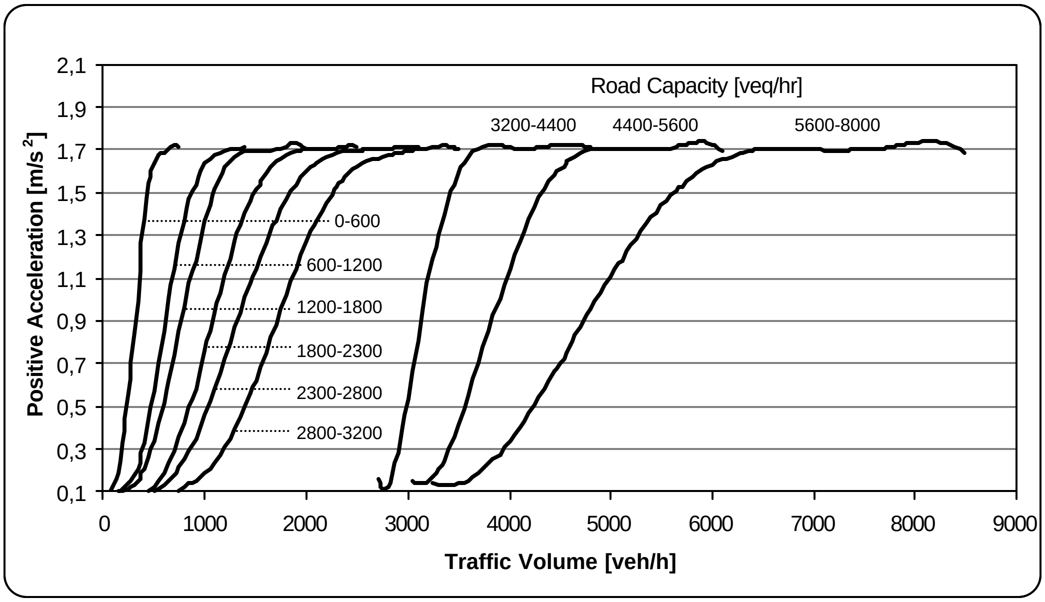

Figure 1. Positive acceleration as a function of traffic volume and road capacity

It may be appreciated from this figure that the maximum value is 1.7 m/s^2 and a value equal to 10% of this maximum has been used as the natural acceleration noise.

2.3 Estimating emissions from both average speed and positive mean acceleration

The incorporation of acceleration as an important variable in estimating emission factors has been widely reported in the specialized international literature (Cadle, 2000; Holmén et al, 1998, Ross et al, 1998; Shayler et al, 1997; Watson, 1995). Most of the authors support the hypothesis establishing that the average speed is not a sufficient parameter for adequately determining the exhaust emission levels in transient conditions (Bratt et al, 1999). However, there are scarce models proposing a more adequate method as an alternative approach to the traditional one based on speed (Sturm et al, 1997).

In order to determine the effect of speed and acceleration in the emissions of light and medium sized vehicles using gasoline as fuel, the data generated by an IM-240 measurement unit have been processed second by second. Both catalytic and non-catalytic vehicles were used subject to five driving cycles with mean speeds of 30, 46, 47, 55 and 73 km/hr respectively. Each one of the five cycles had a total duration time of 240 seconds (Corvalán et al, 2002). An example of this type of information is shown in the following graphic:

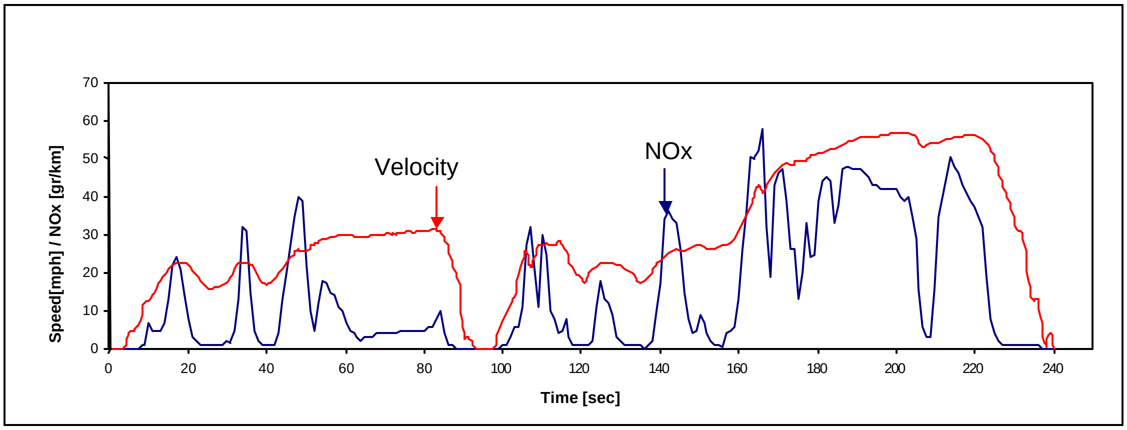

Figure 2. Velocity Curves v/s emission of NOx for IM240 cycle
(The NOx values have been altered in order to adjust to the scale)

A process of analysis of the data available was established, which permitted the obtainment of about 16 registries per trial (each registry includes: mean speed, mean acceleration, travel time, distance traveled, NOx, HC, and CO). In total, 1,000 experimental points were processed corresponding to 60 trials from 14 catalytic and non-catalytic passenger cars.

The type of results obtained indicate that NOx emission is strongly dependent on acceleration while this same pollutant shows a poor correlation with the speed variable. A similar tendency is observed in the work of Sturm et al (1997). The results obtained from non-catalytic vehicles are shown on Figures 3 and 4.

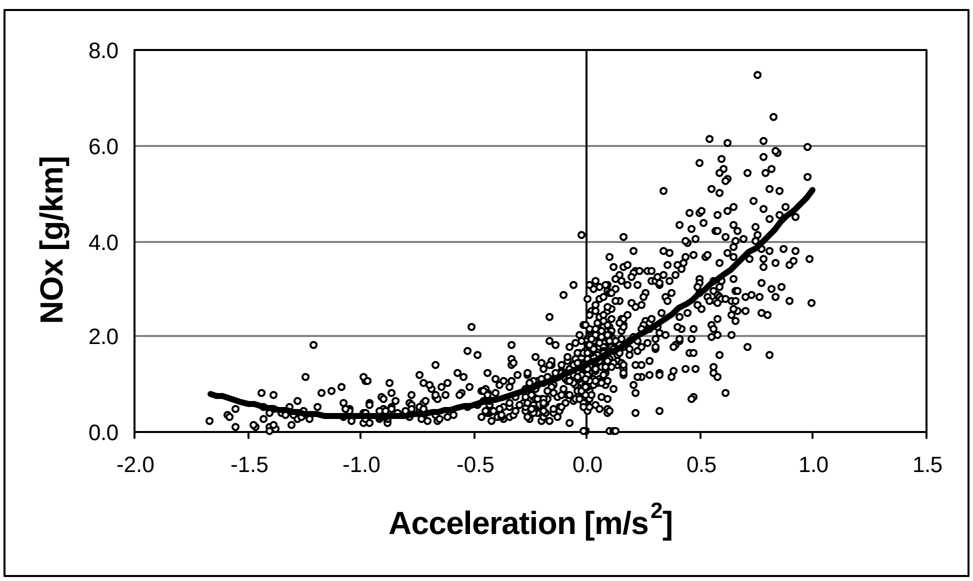

Figure 3. Emission of NOx in function of acceleration
(non-catalytic vehicles)

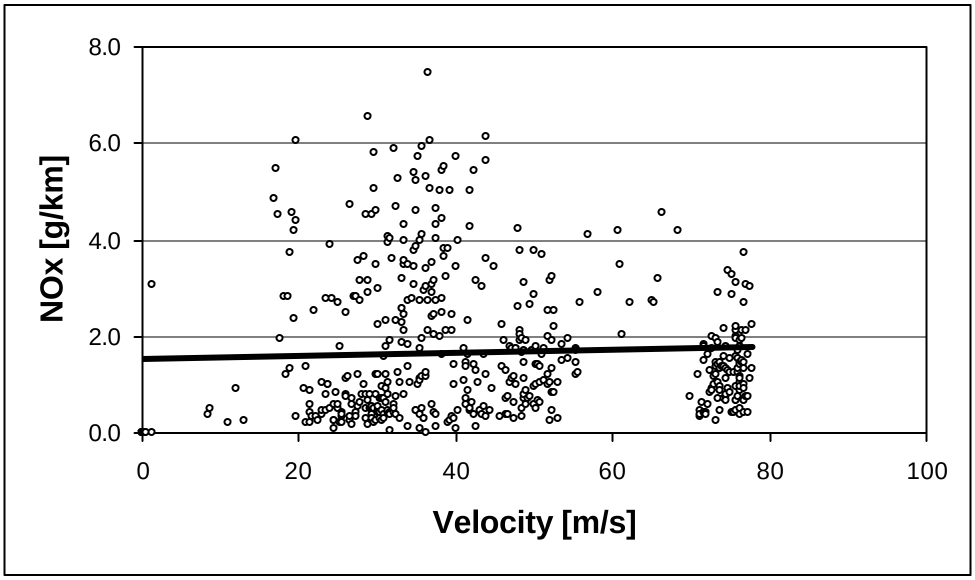

Figure 4. Emission of NOx in function of velocity
(non-catalytic vehicles)

The experimental points represented in the previous graphics permit to analyze the importance of mean speed and the positive mean acceleration (PMA) for each one of the three pollutants considered, for three-way catalytic and non-catalytic vehicles. The analysis was made through regression curves (the best fit tendency with polynomials or powers) and through neuronal networks. A summary of the results is shown on Table 1 indicating the number of points composing each sample, the correlation level (R^2) of the regression curves and the importance percentage in the emission explanation for each variable according to neuronal networks. In the last case, values within brackets indicate the variable degree.

Table 1. Statistic analysis of gaseous emissions in function of velocity (Vel) and acceleration (Acc)

Vehicle type	Pollutant	Best fit tendency			Neuronal network				
		Points	Vel	Acc	Points	Vel(1)	Acc(1)	Acc(2)	Acc(3)
		#	R^2	R^2	#	%	%	%	%
Non-cat	NOx	524	0.047	0.625	693	--	61	30	8
	CO	518	0.354	0.240	660	12	15	34	38
	HC	518	0.527	0.290	673	30	--	33	38
Cat	NOx	768	0.025	0.325	502	--	72	23	5
	CO	763	0.216	0.094	473	--	17	50	34
	HC	763	0.094	0.192	477	--	21	37	42

The fit value indicated in the fourth column corresponds to the reference used in the actual emission factors representing the vehicle fleet in Santiago, Chile, based on the mean travel velocity. CO shows the best fit level, while NOx presents the worst correlation in both vehicle types. HC shows a very good correlation in conventional vehicles (R^2=0.53), but it decreases notably for three-way catalytic vehicles (R^2=0.09). A comparison with the correlation levels indicated in the fifth column, using acceleration as the control parameter, shows that NOx improves notoriously for both vehicle types, whereas emissions of HC and CO continue to be better explained by velocity.

The neuronal networks analysis indicated that the best percentage of importance in the explanation of emissions is attributed to NOx (61% and 72%). Velocity appears weekly linked to emission of CO and HC in conventional vehicles, while there was no relationship detected between velocity and NOx for the total points of the sample. According to this type of analysis, emissions seem to be better explained by acceleration for the three gases considered.

3. DISCUSSION

According to the results obtained, it is important to incorporate acceleration as a variable for estimating NOx emissions from urban land vehicle sources. This results in changing the present emission factors depending on the mean travel velocity for curves in function of positive mean acceleration.

However, the difficulty in getting accurate acceleration values in complex road systems makes it difficult for an estimating scheme based only on acceleration to be applied. Due to this, a mixed calculation method is proposed in which the emission values obtained are corrected by the positive mean acceleration.

The incorporation of the acceleration variable in the estimation of NOx emissions is highly dependant upon the degree of vehicle flow in the road system. For this reason it is necessary to develop specific methodologies for scenarios with a high vehicle flow and for free or moderate vehicle flow conditions.

The effect of acceleration is greater at lower speeds. For this reason the use of different correction factors according to the speed range is recommended. In this study a cut at 55 km/hr is considered, factors from 0 to 55 km/hr and from 55 up to 100 km/hr are proposed. These results are also dependant upon the vehicle emissions control technology. In this particular case, conventional and three-way catalytic vehicles are considered separately.

A preliminary estimation of emissions using acceleration as the correction element for mean speed, at a traffic activity time of high vehicle flow for the case of Santiago, indicates a 34% NOx emission increase, compared with calculation only based on speed. This result changes to 4% NOx reduction when considering a moderate traffic activity time (no high vehicle flow) for the same pollutant.

4. ACKNOWLEDGMENTS

This study was carried out thanks to the financing provided by the Chilean Government through the Environmental Unit of SECTRA (*Unidad de Medio Ambiente de SECTRA*). We are also thankful to the work carried out by José Escárate and Felipe Farfán who contributed with their support to the experimental data processing.

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