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Calibrating Fuel Consumption and Emission Models for Modern Vehicles

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NOTE:

This paper is related to the analysis methodology used in the SIDRA INTERSECTION and SIDRA TRIP software packages.

CALIBRATING FUEL CONSUMPTION AND EMISSION MODELS FOR MODERN VEHICLES

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ABSTRACT

Estimation of fuel consumption and pollutant emissions for evaluating traffic conditions is useful for environmental assessment in traffic design, operations and planning. This also forms the basis of operating cost modelling. Fuel consumption and emission (CO_2, CO, HC, NO_x) models of four levels of aggregation were developed by the first author and his colleagues at the Australian Road Research Board in the 1980s. The four-mode elemental (modal) and the more detailed instantaneous forms of the model are implemented in the SIDRA INTERSECTION and SIDRA TRIP software packages. Vehicle parameters used by these models are being calibrated using data for a modern vehicle fleet for use in future versions of these software packages. For this purpose, an empirical database (NISE 2) incorporating a large range of fuel consumption and emission data for about 400 vehicles representing a cross section of typical vehicles on Australian metropolitan roads is being used. Data were collected in a vehicle emissions test laboratory using a real-world driving cycle called CUEDC-P (composite urban emission drive cycle for petrol vehicles) developed from Australian driving pattern data collected in the field. This paper describes the models and the calibration method used, and presents results for a medium-size passenger car.

INTRODUCTION

Estimation of fuel consumption and pollutant emissions for evaluating traffic conditions is useful for environmental assessment in traffic design, operations and planning. This also forms the basis of operating cost modelling. This paper describes the fuel consumption and emission (CO_2, CO, HC, NO_x) models used in the SIDRA INTERSECTION and the SIDRA TRIP software packages (Akcelik & Associates 2007, 2011), and discusses an effort to calibrate the vehicle parameters used by these models using data for a modern vehicle fleet.

SIDRA TRIP uses the instantaneous form and SIDRA INTERSECTION uses the four-mode elemental (modal) form of the same model which is based on extensive research (Akçelik 1980, 1981, 1983, 1985, 1986a,b, 1989, 2006; Akçelik, et al 1983; Akçelik and Besley 2001, 2003; Akçelik and Biggs 1985; Biggs 1988; Biggs and Akçelik 1985, 1986a,b; Bowyer, Akçelik and Biggs 1985, 1986; Holyoake 1985; Luk and Akçelik 1983; Taylor and Young 1996). The instantaneous form of the model is described in this paper.

This model provides highly accurate fuel consumption estimates for traffic analysis since there is no aggregation (simplification) involved in terms of traffic information, i.e. variables such as average travel speed, average running speed and number of stops are not used. However, it has been recognized that it is necessary to update vehicle parameters used by the model, especially for emission estimates, in order to reflect more recent changes in vehicle characteristics (rated engine power, catalyst loading and composition, engine management system, etc.) and fleet composition (e.g. see Unal, et al 2003).

For calibrating vehicle parameters used by the model, an empirical database (NISE 2) incorporating a large range of fuel consumption and emission data for about 400 vehicles representing a cross section of typical vehicles on Australian metropolitan roads is being used. Data were collected in a vehicle emissions test laboratory using a real-world driving cycle called CUEDC-P (composite urban emission drive cycle for petrol vehicles) developed from Australian driving pattern data collected in the field. This paper presents the model calibration results for a medium-size passenger car (Toyota Corolla Ascent) and compares the vehicle parameters with those used for a similar default vehicle in SIDRA TRIP.

MODEL PARAMETERS

The fuel consumption and emission models use two groups of parameters, namely vehicle parameters, and traffic and road parameters.

Vehicle parameters include loaded mass, idle fuel or emission rates, and fuel or emission efficiency rates. The vehicle parameters used in the fuel consumption and emission models are derived considering fleet composition (percentage of vehicle kilometres for each vehicle type) with more detailed vehicle data including fuel type (% diesel), maximum engine power, power to weight ratio, number of wheels and tyre diameter, rolling resistance factor, frontal area and the aerodynamic drag coefficient.

In SIDRA INTERSECTION, fuel consumption, emissions and cost are calculated for *light and heavy vehicles*. A heavy vehicle is defined as any vehicle with more than two axles or with dual tyres on the rear axle. The US Highway Capacity Manual defines a heavy vehicle as "a vehicle with more than four wheels touching the pavement during normal operation" (TRB 2000). Thus, buses, trucks, semi-trailers (articulated vehicles), cars towing trailers or caravans, tractors and other slow-moving vehicles are classified as heavy vehicles. All other vehicles are defined as light vehicles (cars, vans, small trucks).

In SIDRA TRIP, vehicle parameters can be specified for individual vehicles. Default vehicles consist of a light vehicle, a heavy vehicle and a passenger car.

Default values of vehicle parameters in SIDRA INTERSECTION and SIDRA TRIP are based on those reported in Bowyer, Akçelik and Biggs (1985) for the fuel consumption model, and those derived by Holyoake (1985) for the emission model. Detailed data used for the selection of representative light and heavy vehicles are given in an earlier paper (Akçelik and Besley 2003) and in software user guides. Model parameters for fuel consumption and emission models for the default passenger car in SIDRA TRIP are given in *Table 1*.

Traffic and road parameters used directly in the SIDRA model for fuel and emission estimation include speed, acceleration rate and grade parameters. The polynomial acceleration model used in SIDRA INTERSECTION and SIDRA TRIP is described in detail in Akçelik and Besley (2001).

SIDRA TRIP traffic data is based on microscopic (usually second-by-second) *trip data from an instrumented car*, e.g. data collected using a Global positioning System (GPS) data logger, or microscopic trip data representing a *standard drive cycle*, or drive-cycle data generated by the user to represent a series of *traffic events* which are specified in terms of cruise, idle and speed change (acceleration or deceleration) with initial and final speeds given for each event.

Table 1 - Parameters for fuel consumption and emission models for the default passenger car in SIDRA TRIP

Parameter	Description	Units for Fuel	Units for Emissions	**Fuel**	**CO**	**HC**	**NO_x**
α	Idle fuel consumption or emission rate	mL/s	mg/s	0.361	13.889	2.222	0.556
f_i	Idle fuel consumption or emission rate, $f_i = 3600\ \alpha$	mL/h	g/h	1300.0	50.0	8.0	2.0
A	Drag fuel consumption or emission parameter, mainly related to rolling resistance **A = 1000 c_1**	mL/km	mg/km	20.0	1000.0	0.000	0.000
B	Drag fuel consumption or emission parameter mainly related to aerodynamic drag **B = c_2 / 0.01296**	(mL/km)/ (km/h)^2	(mg/km)/ (km/h)^2	0.0050	0.000	0.020	0.060
b_1	$b_1 = c_1 / \beta_1$	kN	kN	0.2222	66.7	0.0	0.0
b_2	$b_2 = c_2 / \beta_1$	kN/(m/s)^2	kN/(m/s)^2	0.00072	0.0	0.0	0.78
c_1	$c_1 = A / 1000$	mL/m	mg/m	0.02000	1.000	0.000	0.000
c_2	$c_2 = 0.01296\ B$	(mL/m) /(m/s)^2	(mg/m) /(m/s)^2	0.0000648	0.000	0.00026	0.00078
β_1	Efficiency parameter	mL/kJ	mg/kJ	0.0900	15.00	0.000	1.000
β_2	Energy-acceleration efficiency parameter	mL/ (kJ.m/s^2)	mg/ (kJ.m/s^2)	0.0300	25.00	4.00	0.200
M_v	Average vehicle mass	kg		1250			
P_{max}	Maximum power	kW		80			
f_{CO2}	CO_2 emission rate	g/mL		2.50			

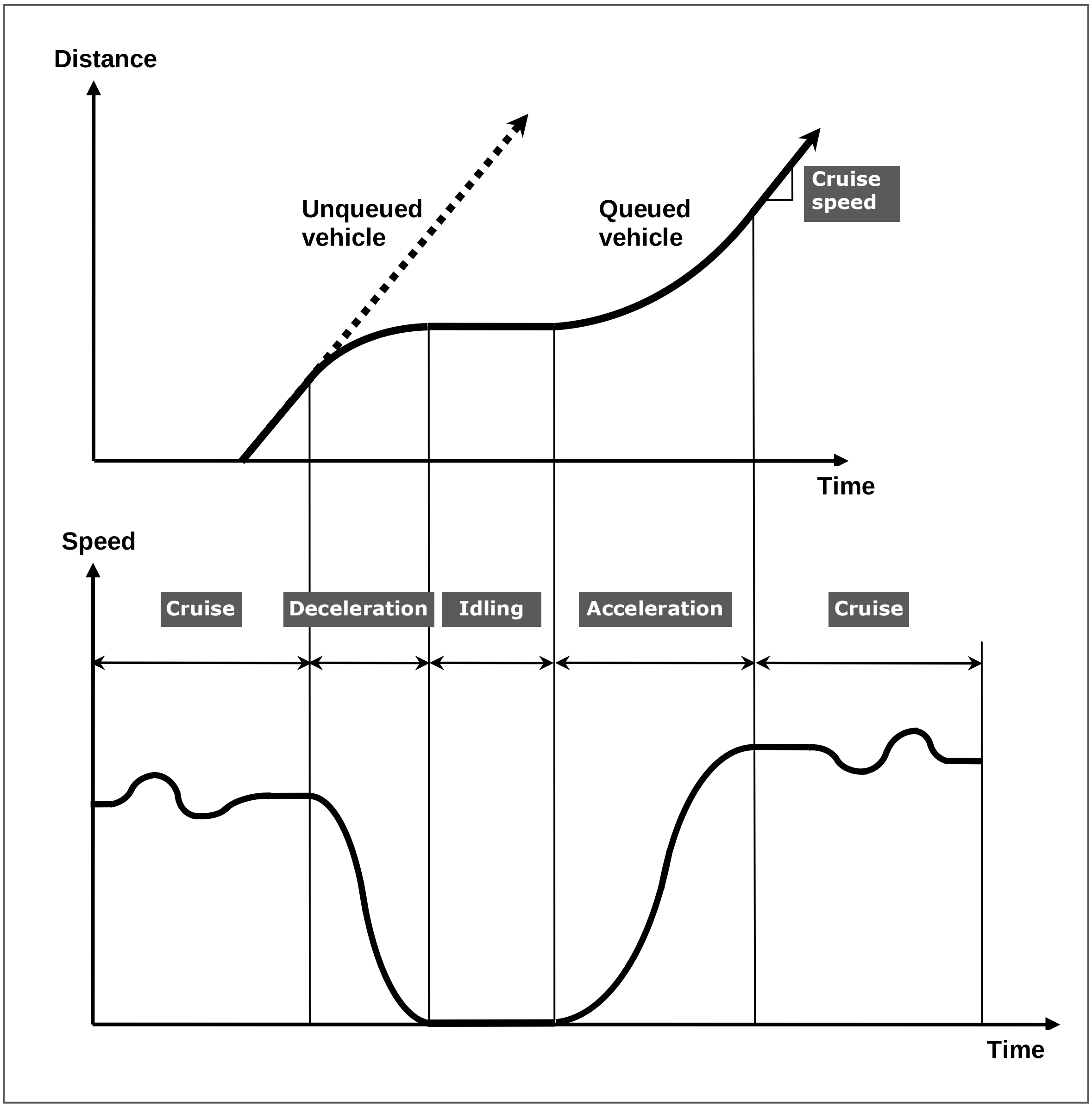

Figure 1 - Drive cycle during a stop - start manoeuvre (example)

In all cases, SIDRA TRIP generates instantaneous speed and acceleration rate values for use by the microscopic simulation model. Fuel consumption, pollutant emissions and operating cost are calculated for each simulation interval (time step), and the results added together for each drive-cycle element (event) and for the entire trip.

SIDRA INTERSECTION uses a macroscopic four-mode elemental (modal) model. For each lane of traffic, the traffic model derives drive cycles consisting of a series of *cruise*, *acceleration*, *deceleration* and *idling (stopped) time* elements (*Figure 1*) for specific traffic conditions represented by intersection geometry, traffic control and demand flows based on data supplied by the user. Thus, the drive cycles generated by SIDRA INTERSECTION are very different for different intersection types (signalised, sign-controlled, roundabout), for different signal phasing arrangements, for different signal timings for a given phasing arrangement, for give-way (yield) and stop control (two-way or all-way), and for different congestion levels.

Fuel consumption and emission values are calculated for each of the four driving modes, and the results are added together for the entire driving manoeuvre from entry to the approach road at a point upstream of the intersection to a point on the downstream exit road. The model is applied to queued (stopped) and unqueued (unstopped) vehicles, and light and heavy vehicles in each lane separately, and then the total values are calculated for all traffic using the lane. For unqueued vehicles, only the cruise and geometric stop (intersection negotiation) components apply. For queued vehicles, the drive cycles are determined distinguishing between major stops, queue move-ups (repeated stops in queue) and geometric stops (slow-down or full stop in the absence of any other vehicle).

The instantaneous model of fuel consumption is described in the following section.

MODEL for FUEL CONSUMPTION

The SIDRA fuel consumption model can be expressed in terms of the energy, power or tractive force required by the vehicle. The instantaneous model estimates the fuel consumption rate (mL/s) as a value per unit time measured at any instant during the trip as a function of the tractive power required by the vehicle:

$$f_t = \alpha + \beta_1 P_T + [\beta_2 a P_I]_{a>0} \quad \textit{for } P_T > 0 \tag{1}$$
$$= \alpha \quad \textit{for } P_T \leq 0$$

$$P_T = \mathit{min}\,(P_{max}, P_C + P_I + P_G) \tag{2}$$

$$P_C = b_1 v + b_2 v^3 \tag{3}$$

$$P_I = M_v a v / 1000 \tag{4}$$

$$P_G = 9.81 M_v (G/100) v / 1000 \tag{5}$$

$$\alpha = f_i /3600 \tag{6}$$

where

f_t = instantaneous fuel consumption rate (mL/s),
P_T = total tractive power (kilowatts, kW),
P_{max}= maximum engine power (kW),
P_C = *cruise* component of total power (kW),
P_I = *inertia* component of total power (kW),
P_G = *grade* component of total power (kW),
R_T = total tractive force (kilonewtons, kN) required to drive the vehicle,
G = road grade (per cent), negative if downhill,
M_v = vehicle mass (kg) including occupants and any other load,
v = instantaneous speed (m/s) = v (km/h) / 3.6
a = instantaneous acceleration rate (m/s^2), negative for deceleration,
α = constant idle fuel consumption rate (mL/s), which applies during all modes of driving (as an estimate of fuel used to maintain engine operation),

f_i = $3600\ \alpha$ = constant idle fuel consumption rate in mL/h,

b_1 = vehicle parameter related mainly to the rolling resistance (kN),

b_2 = vehicle parameter related mainly to the aerodynamic drag (kN/(m/s) ^{2}),

β_1 = the efficiency parameter which relates fuel consumed to the total power provided by the engine, it can be shown to be fuel consumption per unit of energy (mL/kJ or g/kJ), and

β_2 = the efficiency parameter which relates fuel consumed during positive acceleration to the product of acceleration rate and inertia power when n = 1.0 (mL/(kJ.m/s^2) or g/(kJ.m/s^2)).

The instantaneous cruise fuel consumption rate (a = 0, P_I = 0) on a on a level road (G = 0, P_G = 0) is given by:

$$f_{ct} = \alpha + \beta_1 P_C \tag{7a}$$
$$f_{ct} = \alpha + \beta_1 (b_1 v + b_2 v^3) \tag{7b}$$
$$f_{ct} = \alpha + c_1 v + c_2 v^3 \tag{7c}$$

where

$$c_1 = b_1 \beta_1 \tag{8a}$$
$$c_2 = b_2 \beta_1 \tag{8b}$$

where the parameter units are mL/m for c_1 and (mL/m)/(m/s)^2 for c_2.

Equation (7c) is used as an important part of the model calibration method for fuel consumption. After parameters c_1, c_2 and β_1 are determined through calibration, the following model parameters are calculated.

Parameters A and B specified as input for software are calculated from:

$$A = 1000\ c_1 \tag{9a}$$

$$B = c_2 / 0.01296 \tag{9b}$$

where the parameter units are mL/km for A and (mL/km)/(km/h)^2 for B.

Parameters b_1 and b_2 are determined indirectly from:

$$b_1 = c_1 / \beta_1 \quad \textit{if } \beta_1 > 0$$
$$= 0 \quad \textit{if } \beta_1 = 0 \tag{10a}$$

$$b_2 = c_2 / \beta_1 \quad \textit{if } \beta_1 > 0$$
$$= 0 \quad \textit{if } \beta_1 = 0 \tag{10b}$$

Parameters b_1 and b_2 are determined from *Equations (10a) and (10b)* using c_1 and c_2 values determined for fuel consumption in order to obtain a reasonable representation of drag (cruise) power to be provided by the engine so that the model application for fuel consumption is based on a realistic definition of R_C, P_C, R_T and P_T. Parameters b_1 and b_2 also reflect some component of drag associated with the engine.

The following simpler model is obtained as an alternative model by dropping the (a P_I) term of *Equation (1)*:

$$f_t = \alpha + \beta P_T \quad \text{for } P_T > 0 \tag{11}$$
$$ = \alpha \quad \text{for } P_T \leq 0$$

where parameters are as in *Equation (1)*.

The values of instantaneous *Carbon Dioxide (CO_2)* emission rate (g/s as a value per unit time) are estimated directly from the instantaneous fuel consumption rate:

$$f_t(CO_2) = f_{CO2}\, f_t(fuel) \tag{12}$$

where

$f_t(fuel)$ = fuel consumption rate in mL/s and,

f_{CO2} = CO_2 to Fuel Consumption Rate in grams per millilitre (kg per litre) of fuel (g/mL or kg/L).

The model for estimating the *instantaneous Carbon Monoxide (CO), Hydrocarbons (HC)* and *Nitrogen Oxides (NO_x) emission rates* (mg/s), representing the emission production rate at any instant during the trip determined as a value per unit time, has the same structure as the instantaneous fuel consumption model with different parameters.

MODEL CALIBRATION

There is a substantial amount of empirical vehicle fuel consumption and emission test data available for Australian vehicles. The model calibration results reported in this paper are based on hot running emission data extracted from a test program called the second Australian National In-Service Emissions (NISE 2) vehicle emissions program (DEWHA, 2005; 2009; Smit, Steele and Wilson 2010). The test program provides laboratory test data for about 400 petrol light-duty vehicles on both a second-by-second (modal) basis as well as on an aggregated (bag) basis for different driving cycles, which is a large database (more than 500 hours of test data) compared to international standards.

The calibration results are given for a medium-size passenger car (Toyota Corolla Ascent, model year 2004, 1.8 litre 4 cylinder petrol engine, rated engine power of 100 kW, ADR79/00 certified, automatic transmission) - see *Figure 2*. This vehicle is comparable to the default passenger car used in SIDRA TRIP in terms of vehicle mass and main vehicle type.

The emissions data were collected using a 30-minute real-world driving cycle called the CUEDC-P (Composite Urban Emission Driving Cycle for Petrol vehicles). This cycle was developed from Australian driving pattern data collected in the field. It consists of four phases, or sub-cycles, representing *Residential*, *Arterial*, *Freeway* and *Congested* driving conditions. The "official" CUEDC-P speed-time profile is shown in *Figure 3*. Individual vehicle profiles differ from the official profile and from other vehicle profiles slightly.

A step-wise calibration method was used for determining the values of fuel consumption model parameters summarised in *Table 1*. This method requires definition of four basic driving modes, namely cruise, deceleration, idling and acceleration (*Figure 1*). The definitions based on instantaneous speed and acceleration values are shown in *Table 2*. For the results given in this paper, no data aggregation was applied in defining the basic modes.

Medium-size passenger car: Toyota Corolla Ascent 2004
Mass = 1250 kg, Max. Power = 100 kW

Figure 2 – The test vehicle used for fuel consumption model calibration results reported in this paper

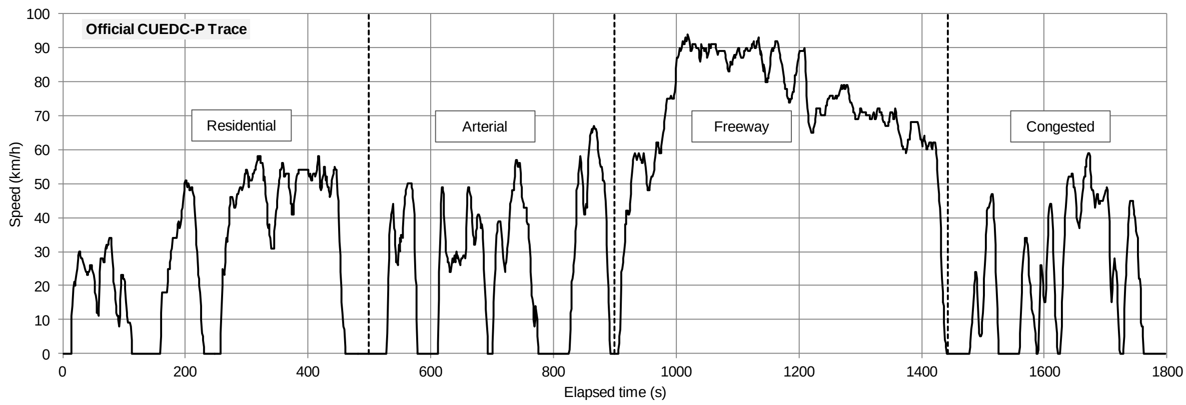

Figure 3 – CUEDC-P Driving Cycle

Table 2 – Definition of four basic driving modes

Driving Mode	Definition
Idling	$v_t = 0$ m/s
Cruise	$v_t > 0$ m/s and $-0.2 \text{ m/s}^2 \leq a_t \leq +0.2 \text{ m/s}^2$
Acceleration	$v_t > 0$ m/s and $a_t > +0.2 \text{ m/s}^2$
Deceleration	$v_t > 0$ m/s and $a_t < -0.2 \text{ m/s}^2$

v_t: speed, a_t: acceleration rate

Two calibration methods were implemented: **Calibration Method 1** which applies to the model expressed by *Equation (1)*, and **Calibration Method 2** which applies to the simpler model expressed by *Equation (11).* Both calibration methods gave satisfactory results for fuel consumption and the results were close. Comments on calibration of emission models are given in the Concluding Remarks section. Testing of both calibration methods will be continued with data for other vehicles. Only the results for Calibration Method 2 are presented in this paper.

Method Used for Fuel Consumption Model Calibration

The model for fuel consumption to determine best values of vehicle parameters α**,** $\mathbf{b_1}$**,** $\mathbf{b_2}$ **and** β in *Equation (11)* was calibrated by carrying out the following steps:

(i) Determine the idle fuel consumption rate, α (mL/s) by measuring fuel consumption while idling. Calculate idling rate, $\mathbf{f_i}$ in mL/h.

(ii) Determine the cruise fuel consumption parameters $\mathbf{c_1}$ and $\mathbf{c_2}$ from regression using cruise fuel consumption data, f_{ct} calculated as follows for speeds between 15 and 120 km/h:

$$f_{ct} - \alpha = c_1 v + c_2 v^3 \tag{13}$$

where α is the idle fuel consumption rate (mL/s) as determined in step (i) and v is the steady cruise speed (m/s) as determined for conditions stated in *Table 2*.

Determine the values of parameters $\mathbf{c_1}$ and $\mathbf{c_2}$ jointly by regression of **v** and $\mathbf{v^3}$ on $(\mathbf{f_{ct}} - \alpha)$ through the origin. Apply the conditions $\mathbf{c_1} \geq 0$ and $\mathbf{c_2} \geq 0$. Calculate parameters **A** and **B** from *Equations (9a) and (9b)* using values of $\mathbf{c_1}$ and $\mathbf{c_2}$ from regression.

(iii) Determine the efficiency parameter β and the rolling resistance and aerodynamic resistance parameters $\mathbf{b_1}$ and $\mathbf{b_2}$ using the instantaneous fuel consumption data. For this purpose, determine the cruise component of fuel (f_{ct}) for each data point using *Equation (13)* with known parameter values (α, c_1 and c_2) as determined in steps (i) and (ii). Calculate the inertial component of fuel consumption using P_I from *Equation (4)* for each data point:

$$f_{It} = f_t - f_{ct} = \beta P_I \qquad \textit{for } P_T > 0 \tag{14}$$

where P_T is the total power from *Equation (2)* used to ensure condition $P_T > 0$ is met.

Apply the following iterative method to determine β, $\mathbf{b_1}$ and $\mathbf{b_2}$:

- start with some initial values of $\mathbf{b_1}$ and $\mathbf{b_2}$ (e.g. the default values given in *Table 1*) to determine P_T from *Equation (2)*,
- determine the value of β by regression of $\mathbf{P_I}$ on $\mathbf{f_{It}}$ through the origin (apply the condition $\beta \geq 0$),
- using β from regression, calculate new values of parameters $\mathbf{b_1}$ and $\mathbf{b_2}$ from *Equations (10a) and (10b)*,
- use the new values of $\mathbf{b_1}$ and $\mathbf{b_2}$ to determine P_T and repeat the estimation process until estimated β (therefore $\mathbf{b_1}$ and $\mathbf{b_2}$) values do not change.

CALIBRATION RESULTS

The fuel consumption model parameters found by implementing the stepwise calibration method described above using data for the medium-size test car (Toyota Corolla Ascent 2004) are summarised in *Table 3*. A comparison with the default passenger car parameters used in SIDRA TRIP is also given in *Table 3*.

Comparing model estimates based on calibrated model parameters for the test car and the model parameters for the SIDRA TRIP default passenger car shown in *Table 3*, it was found that the test car is significantly more efficient indicating 19% lower fuel consumption and CO_2 emission estimates (using the same CO_2 to fuel consumption rate, f_{CO2} = 2.35 g/mL) for the overall drive cycle (all segments). The preliminary results indicate that all emissions (CO, HC and NO_x) are also substantially lower. These results are as expected due to technological improvements in the vehicle fleet since the 1980s.

Using the calibrated test vehicle parameters, fuel consumption rates were estimated with high accuracy in terms of both instantaneous values (differences in the range -0.4 mL/s to +0.4 mL/s) and total values (total error 2.4 mL, or 0.2%). This can be seen from *Figures 4 and 5* which show comparison of estimated and measured fuel consumption rates.

When the parameters optimised for the *overall drive cycle* were used for estimating fuel consumption and CO_2 emission for the *Residential*, *Arterial*, *Freeway* and *Congested* speed-profile segments, both instantaneous values and the total values were still highly accurate (3% error for the Freeway segment and -2% error for the Residential, Arterial and Congested segments together).

Table 3 - Calibrated fuel consumption model parameters for medium-size passenger car (Toyota Corolla Ascent 2004) and SIDRA TRIP default passenger car

Parameter	Description	Units	SIDRA TRIP P.C.	Toyota Corolla	Difference
α	Idle fuel consumption rate	mL/s	0.361	0.2469	-32%
f_i	Idle fuel consumption rate, **$f_i = 3600\ \alpha$**	mL/h	1300	888.8	-32%
A	Drag fuel consumption parameter, mainly related to rolling resistance **$A = 1000\ c_1$**	mL/km	20.0	12.19	-39%
B	Drag fuel consumption parameter mainly related to aerodynamic drag **$B = c_2 / 0.01296$**	(mL/km)/ (km/h)^2	0.0050	0.0036	-28%
b_1	**$b_1 = c_1 / \beta_1$**	kN	0.2222	0.1316	-41%
b_2	**$b_2 = c_2 / \beta_1$**	kN/(m/s)^2	0.00072	0.00050	-31%
c_1	**$c_1 = A / 1000$**	mL/m	0.0200	0.0122	-39%
c_2	**$c_2 = 0.01296\ B$**	(mL/m) /(m/s)^2	0.0000648	0.0000464	-28%
β_1	Efficiency parameter	mL/kJ	0.0900	0.0926	3%
β_2	Energy-acceleration efficiency parameter	mL/(kJ.m/s^2)	0.0300	NA	NA
M_v	Average vehicle mass	kg	1250	1250	0%
P_{max}	Maximum power	kW	80	100	25%
f_{CO2}	CO_2 emission rate	g/mL	2.50	2.35	-6%

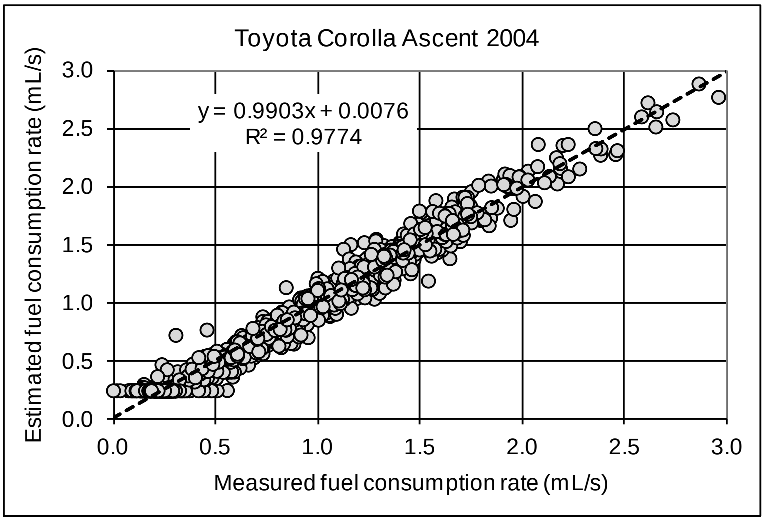

Figure 4 – Estimated vs measured values of instantaneous fuel consumption rates

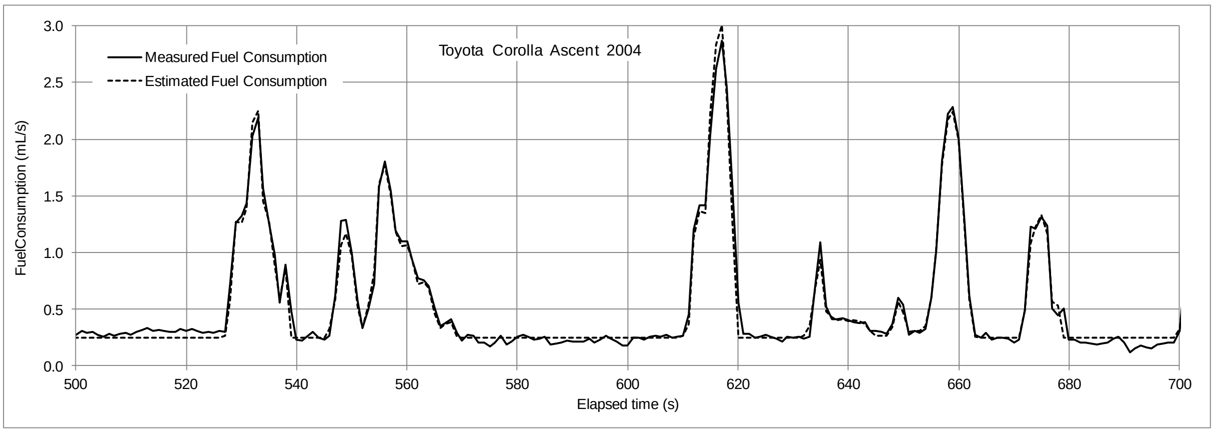

Figure 5 – Sample of time profiles of estimated and measured values of instantaneous fuel consumption rates

CONCLUDING REMARKS

As expected, significant differences have been found in fuel consumption and emission model parameters for the medium-size test vehicle compared with parameters established in the 1980s. Similar results have been obtained for a large passenger car (not presented in this paper). Work is in progress for calibrating the fuel consumption and emission model described in this paper using data for a large number of vehicles. The results will be made available in due course.

While the reliability of fuel consumption estimates has been found to be very high, *large variability has been observed in estimates obtained from emission models optimized for the overall drive cycle. Although the errors in estimates of total emission for the whole drive cycle were small (in the range 7% to 10%), rather large errors were found in total emission values when applied to shorter segments. This will be the subject of further investigation.*

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