DEVELOPMENT OF INSTANTANEOUS CAR FUEL CONSUMPTION MODEL

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Abstract: This paper describes research on the development of instantaneous car fuel consumption model in Bandung. It is an energy-related model that expresses fuel consumption over unit of time, which developed by BOWYER *et al* (1985) in Australia. The objectives of the research were to derive idling fuel consumption, steady speed fuel consumption, and to develop an instantaneous fuel consumption model for typical urban traffic. An accurate fuel flow meter named LC-5100 System from Japan and speed logger recorded from TRL were used to collect data of fuel consumption at idling, and steady speed (no acceleration) on Padalarang - Cileunyi tollroad, Bandung, and urban driving in Bandung's selected route. The test vehicle was Toyota Kijang 1990 with 1486-cc engine capacity.

1. INTRODUCTION

BOWYER *et al* (1985) described a range of fuel consumption models based on a simplified version of ARFCOM. They operate at varying level of aggregation, and are, in decreasing order of aggregation:

1. An energy related instantaneous fuel consumption model
2. A four mode elemental model of fuel consumption
3. A running speed model of fuel consumption
4. An average travel speed model of fuel consumption

In particular, the instantaneous model is an extension of the power model reported by KENT, TOMLIN and POST (1982), the elemental model is a refinement of the form reported by AKCELIK (1983) and the running speed model is similar to the positive energy models developed by WATSON (1981). All four models are inter-related and form part of the same modeling framework. A simpler model is derived from a more detail model, e.g. the elemental model from the instantaneous model, keeping the vehicle characteristics such as mass, drag function and energy efficiency as explicit parameters at all model levels.

BOWYER *et al* (1985) presenting the 'default' model parameters for a typical car. Vehicle characteristics are likely to change over the time, and from country to country, and therefore this particular useful property of the models. The default model parameters have been calibrated using data from special on-road experiments in Melbourne (BIGGS and AKCELIK 1983) and extensive on-road driving data collected in Sydney (TOMLIN *et al* 1983). The default model parameters, which are applicable, are given in Table 1. The default model values do not correspond to a particular car. They are based on limited information available at the time of the analysis.

Table 1. Default Vehicle Parameters for Australia

Parameter	*Default Value*	*Description*
α	0.444	Idle fuel rate in ml/s
f_j	1600	As α but in ml/h
M	1200	Mass in kg
β_1	0.090	Energy efficiency parameter in ml/kJ
β_2	0.045	Energy-acceleration efficiency parameter in ml (kJ.m/s^2)
b_1	0.333	Drag force parameter in kN, mainly related to rolling resistance*
b_2	0.00108	Drag force parameter in kN/(m/s)^2, mainly related to aerodynamic resistance*
$c_1=\beta_1.b_1$	0.030	drag fuel consumption component in ml/m, mainly due to rolling resistance
$c_2=\beta_1.b_2$	9.72×10^{-5}	Drag fuel consumption component in (ml/m)/(m/s)^2 mainly due to aerodynamic resistance
$A=10^3c_1$	30.0	As c_1 but in ml/km
$B=c_2/0.01296$	0.00750	AS c_2 but in (ml/km)/(km/h)^2

*) b_1 and b_2 are also related to the component of drag associated with the engine
Source: BOWYER *et al* (1985)

Vehicle characteristics, traffic conditions are different between countries. Estimation of vehicle parameters using the procedure and method suggested by BOWYER *et al* (1985) have been done in Bandung City using on-road data and the result compared with vehicle parameter in Australia.

2. AN ENERGY-RELATED INSTANTANEOUS CAR FUEL CONSUMPTION MODEL

The instantaneous fuel consumption model can be used to estimate fuel consumption of a vehicle. The instantaneous velocity of a vehicle will be used to simulate the fuel consumption at every short interval. Such a model is appropriate for a microscopic traffic model where fuel consumption is of particular importance.

The instantaneous fuel consumption model estimates fuel consumption from second-by-second speed-time and grade information. This is the most fundamental and accurate fuel consumption model for traffic analyses since there is no aggregation involved in terms of driving information, i.e. such variables as average speed, number of stops, etc. are not used.

Basically, the total force (R_T) required to move the vehicle is the sum of drag force (R_D), inertia force (R_I) and grade force (R_G) in kN (kilonewtons). It can be expressed as:

$$R_T = R_D + R_I + R_G \qquad (1)$$

The drag force (R_D) can be expressed as:

$$R_D = b_1 + b_2v^2 \qquad (2)$$

The inertia force (R_I) can be expressed as:

$$R_I = Ma/1000 \qquad (3)$$

The grade force (R_G) can be expressed as:

$$R_G = 9.81\ M(G/100)/1000 \tag{4}$$

where:

v = speed (dx/dt)
M = vehicle mass in kg, including occupants and other load
a = instantaneous acceleration rate (dv/dt)
G = percent grade, which has a negative value for downhill grades
b_1, b_2 = drag force parameters, related respectively mainly to rolling and aerodynamic resistance, parameter b_1 is roughly proportional to vehicle mass and parameter b_2 is approximately proportional to the frontal area of the vehicle.

Since energy is $dE = R_T.dx$, where R_T is the total tractive force required to drive the vehicle along distance dx, the fundamental relationship which expressed fuel consumption is:

$$dF = \alpha dt + \beta_1 R_T dx + \left[\beta_2 a R_I dx\right]_{a>0} \qquad \text{for } R_T > 0 \tag{5}$$

$$dF = \alpha dt \qquad \text{for } R_T \leq 0 \tag{6}$$

where: dF = increment of fuel consumed (ml) during travel along distance dx (m) and in time dt (s),
α = fuel consumption per unit time while idling in ml/s,
dt = small time increment (s),
β_1 = the efficiency parameter which relates fuel consumed to the energy provided by the engine, i.e. fuel consumption per unit energy (ml/kJ),
β_2 = the efficiency parameter which relates fuel consumed during positive acceleration to the product of inertia energy and acceleration, i.e. fuel consumption per unit of energy-acceleration (ml/(kJ.m/s^2)),
a = instantaneous acceleration (dv/dt) in m/s^2, which has a negative value for slowing down, and
R_T = total tractive force required to drive the vehicle (Equation 1),
dx = small distance increment (m).

The third term in Equation 5 allows for the inefficient use of fuel during periods of high acceleration.

Fuel consumption per unit time (ml/s) can be expressed as:

$$f_t = \frac{dF}{dt} = \alpha + \beta_1 R_T v + \left[\frac{\beta_2 M a^2 v}{1000}\right]_{a>0} \qquad \text{for } R_T > 0 \tag{7}$$

$$f_t = \alpha \qquad \text{for } R_T \leq 0 \tag{8}$$

where the tractive force required is:

$$R_T = b_1 + b_2 v^2 + \frac{Ma}{1000} + 9.81 \times 10^{-5} \quad MG \tag{9}$$

Fuel consumption per unit time for constant speed travel along a level road (a=0, G=0) is obtained from the above equation as:

$$f'_{c,t} = \alpha + \beta_1\left(b_1 + b_2 v^2\right)v = \alpha + c_1 v + c_2 v^3 \tag{10}$$

where: $f'_{c,t}$ = constant speed cruise fuel consumption per unit time (ml/s)
α = fuel consumption per unit time while idling in ml/s,
c_1 = drag fuel consumption component in ml/m

c_2 = drag fuel consumption component in $(ml/m)/(m/s)^2$
v = average steady speed in m/s

From the Equation 1 to 10 above, the parameter such as mass (M), acceleration (a), gradient (G), speed (v) are required to find the vehicle parameters: α, c_1, c_2 and β_1, β_2. BOWYER *et al* (1985) suggested procedures for estimating vehicle parameters and the methods, which can be used to calibrate instantaneous model parameters.

The first parameter is α, which describes the idling fuel rate in ml/s of the vehicle. This parameter can be found by the idling fuel consumption test. Next, steady speed tests can be carried out to find fuel consumption per unit time (Equation 10) along a level road ($a=0$ and $G=0$). Parameter c_1 and c_2 are determined by fitting the regression equation with the value of the constant fixed to α.

The last model parameter to be derived are β_1 and β_2, which can be found from fuel consumption measurements in the urban driving test where $a\neq0$ and $G=0$. These parameters require instantaneous (typically second-by-second) speed, grade and fuel consumption values collected on road.

The work programme has main components as shown in Figure 1. The main part of the work programme consists of determining three elements: idling fuel consumption, steady speed fuel consumption and urban driving fuel consumption. Each part consists of relevant tests to determine parameters for the model.

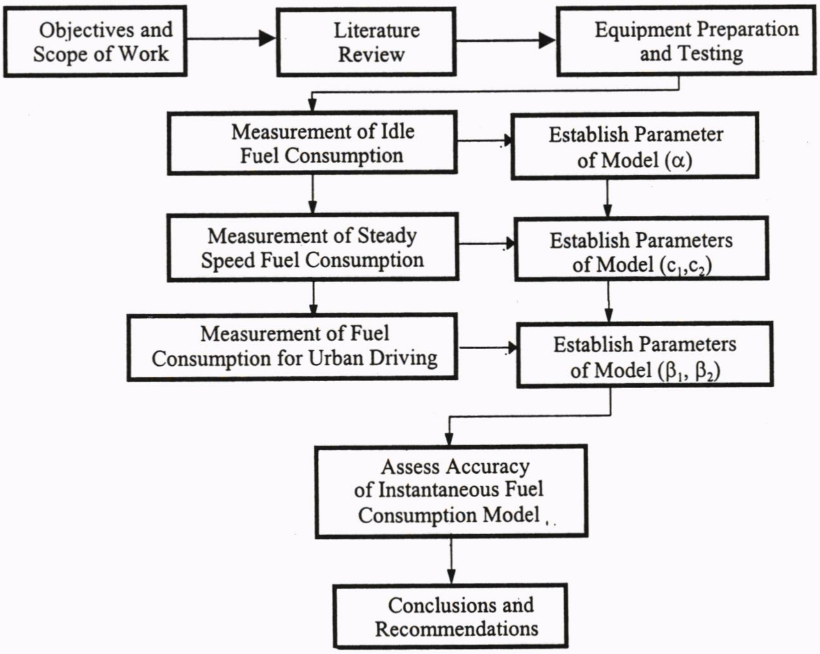


Figure 1. Work Programme

3. TEST VEHICLE AND FUEL CONSUMPTION EQUIPMENTS

The budget and availability limit the chosen test vehicle at the time of the analysis. The test vehicle is Toyota Kijang, which is the major car used and assembly in Jakarta. The other two pieces of equipment that were used on-road driving data collection were the accurate fuel consumption metre and speed measuring equipment.

3.1 The Test Vehicle

A petrol-driven, white Toyota Kijang from 1990 with a 1486-cc engine capacity and manual transmission (4 speeds) with double-blower air conditioning was used as the test vehicle. This vehicle had run about 130,000 km and it was in good condition. Before the test begun, this vehicle was serviced first.

The weight of this vehicle, with full petrol tank, all tools, LC-5100 system, logger, external battery and carrying driver and two observers, is 1,663 kg. Tyre pressure was checked at 28-psi front and 30-psi rear wheels.

3.2 Fuel Consumption Equipment

The fuel consumption equipment (LC-5100 System) made in Japan was installed in the vehicle. There are two main units in the equipment:

1. The control panel housed in the passenger compartment, which gave information about speed, distance, time, and fuel consumption. This information was printed out on special paper six cm wide
2. The fuel flow detector installed under the bonnet between the fuel pump and carburetor. The fuel consumption was measured to an accuracy of 0.1 cc.

3.3 Speed Measuring Equipment

An accurate distance logger was fitted to vehicle. A 12 volt-lead-acid battery provides power. The sensor was fitted permanently into the speedometer cable about 0.3 meters from the speedometer itself. It was attached to the switch box by a sturdy, three-pin connector so that the logger, switch box and battery could all be easily removed from the vehicle.

The sensor produced five pulses per revolution of the cable with a mark-space ratio of approximately one to one. A calibration check indicated 3,342 pulses per kilometre of travel (one pulse per 0.299 metres).

The logger memory was sufficient for several hours of data logging and a number of separate runs could be stored at any one time. Data was downloaded from the logger to a PC using a cable that connects to the serial port. The process was controlled by the easily used, menu-driven program FW1000.EXE. The first produced a binary data file that it could converted to standard ASCII format. The ASCII file could be readily imported into a spreadsheet.

4. SELECTION OF ROUTES

The road network in Bandung was generally marked by narrow roads (two lanes two way) and short distances between intersections. The average speed on primary arterial was 27 kph (MBUDP, 1993). Because of preferably more level terrain, fuel consumption measurements were made in the central and southern parts of Bandung.

For the steady-speed fuel consumption experiment, the selected section of route was required to fulfill the following criteria:
a) uniform,
b) straight,
c) level,
d) with a good bituminous or concrete pavement,
e) without interference from other traffic, and
f) without speed restrictions.

A section of the tollway road between Pasir Koja – Moh. Toha which is part of the Padalarang - Cileunyi tollroad, was selected to meet the required criteria. The section is 5 km long and has concrete pavement. An exemption from the tollway speed limits was needed to be able to carry out tests at a range of constant speeds.

For the urban driving fuel consumption experiment, the criteria for choosing a route were:
a) typical of Bandung,
b) level (the effect of any small gradients was reduced by having a closed circuit),
c) with a bituminous pavement in average condition,
d) with a variety of traffic situations,
e) with a range of traffic volumes,
f) having a typical mix of vehicles and drivers.

To meet these criteria a route in Central Bandung was selected. Figure 2 shows a map with the route. The loop route included five signalised intersections, four unsignalised intersections, both one and two-way roads without a median and two railway crossings. The total length was 4.2 km. Table 2 describes the road sections.

Table 2. Description of Sub Links of Selected Urban Route

ROAD SUB LINK	MOVEMENT	NO.OF LANES	MEDIAN	LENGTH (KM)
Jalan Merdeka (railway crossing)	One Way	4 Lane	No	1.2
Jalan Lembong	One Way	4 Lane	No	0.4
Jalan Veteran	One Way	4 Lane	No	0.6
Jalan Sunda (railway crossing)	One Way	4 Lane	No	0.5
Jalan Sumbawa	One Way	2 Lane	No	0.8
Jalan Sulawesi	One Way	2 Lane	No	0.4
Jalan Martadinata	Two Way	4 Lane	No	0.3
			TOTAL	4.2

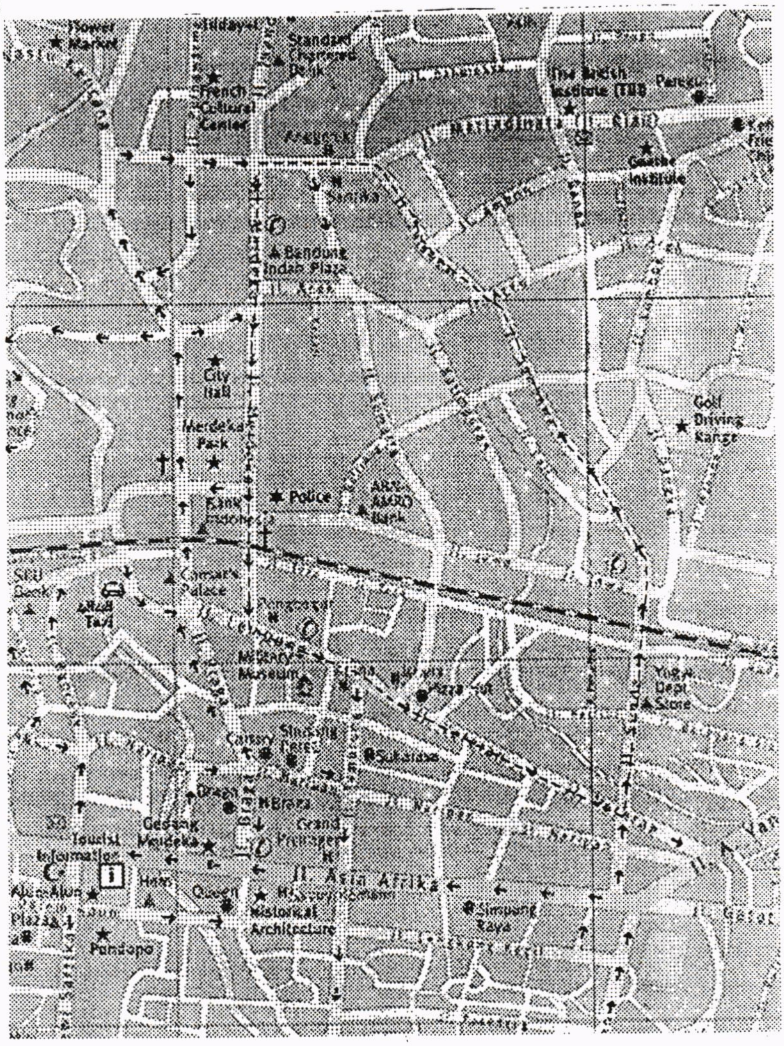
Unfortunately, because most of the roads were operating as one way streets, the survey could only be carried out in one direction.

5. ON-ROAD FUEL CONSUMPTION TEST

The three different type of tests were conducted to found the representative vehicle parameters. The tests are:

1. Idling fuel consumption test
2. Steady speed fuel consumption test
3. Urban driving fuel consumption test

The same driver and the same observer carried out all the tests. The tests were conducted in three days, one day for steady speed test and two days for urban test. The idling tests were conducted between the steady speed and urban test. The tests were done in May 1996 in Bandung



-----> : selection route

Figure 2. Selected Route Representing Bandung Traffic Condition

5.1 Idling Fuel Consumption Test

The idling fuel consumption is a fuel consumed by the engine to maintain engine operation. The fuel consumed by an idling vehicle will be influenced both the engine size and idling rate. No accessories on e.g. air conditioning, lights during the test.

To collect data for idling fuel consumption from the vehicle, the experiment was conducted with a warm engine. The LC-5100 System equipment was set to automatically print out the fuel consumption in cc every second, 10 seconds, and 100 seconds. When the value appeared steady, the total idle fuel consumption was taken as the average.

Table 3 shows the eleven tests of idling fuel consumption. As is clearly seen that there was a little different of idle fuel consumption rate of the test vehicle for a different type of test. The idle fuel consumption of the test vehicle is 0.18 ml/sec with standard error ± 0.00 ml/sec. This value is statistically significant with level of confident 95% and will be used in the instantaneous fuel consumption model.

Table 3. Idle Fuel Consumption

No	Type of Test	Total Time (sec)	Total Fuel Consumption (ml)	Average Fuel Consumption (ml/sec)
1	per sec	17	2.9	0.17
2	per sec	30	5.3	0.18
3	per 10 sec	60	10.9	0.18
4	per 10 sec	30	5.3	0.18
5	per 10 sec	60	10.6	0.18
6	per 10 sec	60	10.6	0.18
7	per 10 sec	60	10.3	0.17
8	per 10 sec	100	17.6	0.18
9	per 100 sec	300	52.7	0.18
10	per 100 sec	300	53.4	0.18
11	per 100 sec	300	53.7	0.18
			Average	**0.18 ± 0.00**

5.2 Steady Speed Fuel Consumption Test

This test gave the parameters c_1 and c_2. BOWYER *et al* (1985) suggested measuring fuel consumption at steady speeds between 4 and 33 m/s (15 and 120 km/h) on a level road. When collecting this data, the gear used at a given speed should be similar for automatic and manual vehicles. This corresponded to the use of a higher gear (thus lower engine revolutions) for constant speed driving compared with the gear used when the vehicle was accelerating. This was typical for traffic situations where vehicles had to maintain a lower steady speed. The effect of the use of a lower gear during acceleration is however accounted for in the model.

These measurements begun with test at 100 km/h in each direction (east and west direction) and they were repeated at progressively lower speed down to 20 km/h. The fuel consumption data were printed out every 10 seconds and about 150 second data were collected each run. With one run in each direction, a total of 18 tests would be carried out. The variables to be recorded were speed (in kph), time (in seconds), distance (in metres) and fuel consumption (in cc).

The steady speed fuel consumption tests were conducted on the tollway to eliminate the traffic influence. During the test, the speedometer was used to determine the vehicle speeds. After all the tests were finished, the speed data from the logger record indicated small differences between logger speed and speedometer. These differences can be seen in Table 4. The speedometer indicated about 10% higher speeds than the logger did. The 10%

higher can be explained for the safety reason. In the factory, the car speedometer was set up about 10% higher than the "real" speed.

These differences also arose because of the different measuring methods used by the speedometer and logger. Both the speedometer and the logger used the same speedometer cable, so the effect of wheels and cable rotation can be ignored. In the subsequent analyses, it has been assumed that the logger speeds are accurate. Some reasons why the logger is more accurate than the speedometer are the driving could be wrong when reading speedometer and the speedometer is an analog device. For further analysis, the logger speed will be used.

In Table 4, the fuel consumption unit was converted from ml/sec to ml/km. These values were calculated from fuel consumption in ml/sec divided by speed in km/sec. The relationship between fuel consumption in ml/km and steady speed in km/h is shown in Figure 3. The relationship is a U-shaped curve with the minimum value of just under 80 ml/km at speed around 45 km/hour.

Also shown in Figure 3 is the gears used during the test. At the speed of 33.62 km/h, fuel consumption was measured in both 3rd and 4th gears. The fuel consumption at 33.62 km/h in the 4th gear was lowest value of fuel consumption measured at 63.40 ml/km. However, the 4th gear (marked as "x" in Figure 3) was too high for normal use at this speed and will not be used for further analysis.

Table 4. Steady-speed Fuel Consumption in ml/km

Average Speedometer Speed (km/h)	**Average Logger Speed (km/h)**	**Average Fuel Consumption with fourth gear (ml/km)**	**Average Fuel Consumption with third gear (ml/km)**	**Average Fuel Consumption with second gear (ml/km)**
20	15.22	-	-	139.26
30	24.51	-	104.81	-
40	33.62	63.40	85.51	-
50	43.58	77.99	-	-
60	53.39	79.73	-	-
70	62.88	92.08	-	-
80	72.17	109.01	-	-
90	81.26	138.25	-	-
100	89.65	143.99	-	-

5.3 Urban Driving Fuel Consumption Test

This test conducted in the selected route in Bandung about 4-km length. One test was travel along the route from the starting point and finished at the same point in about 15 minutes. The driver is told to follow the traffic stream and drive the vehicle normally. The speed slows down on the railway crossing, intersection, etc.

The logger was started first, and after about 10 seconds, the fuel record was started. The LC-500 System recorded the vehicle fuel consumption rate about 30 seconds before the vehicle started moving.

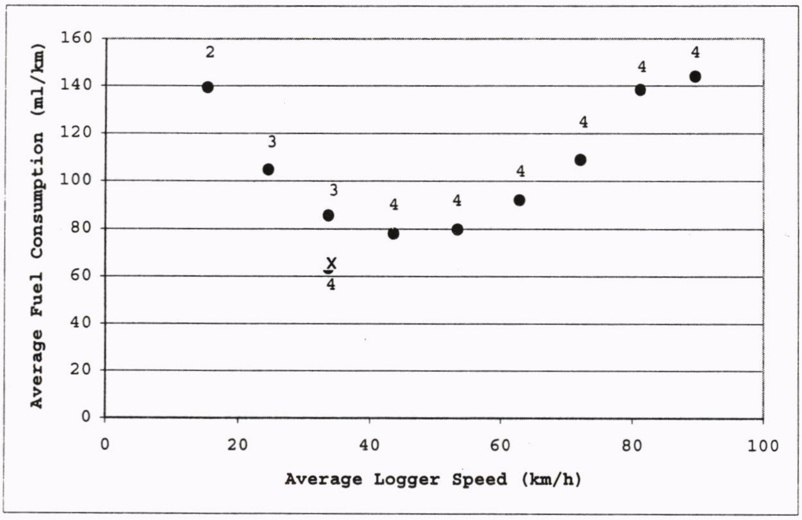


Figure 3. Resume of Steady Speed Fuel Consumption

The instrumented vehicle traveled around the loop at the prevailing traffic speed. It took approximately 15 minutes to complete the loop. With the fuel consumption data printed out every 10 seconds, some 90 data points were obtained per loop. The speed logger recorded time-distance data at every second to give about 900 data points per loop.

Table 5 below shows the result of the urban driving fuel consumption tests. Nine runs were carried out starting between 05:46 and 12:27 hours. The total count is the total number of pulses counted by the logger. The last row in Table 5 shows how much fuel the test vehicle consumed. From Table 5, the minimum total fuel consumed occurred on test number 1 (5.46am) and the maximum occurred at test number 8 (11.28am). The recorded distances around the test circuit varied very little from one run to another.

Table 5. Urban Driving Fuel Consumption Test

	Number of Run								
	1	2	3	4	5	6	7	8	9
Starting Time	5:46	5:57	7:11	7:27	8:28	9:27	10:28	11:28	12:27
Total Count (pulse)	12,853	12,849	12,870	12,859	12,862	12,867	12,862	12,888	12,857
Total Travel Time (sec)	402	396	650	541	751	701	634	882	712
Total Running Time (sec)	375	365	546	519	610	535	530	706	616
Total Idle Fuel (ml)	21.5	27.4	51.0	27.5	45.1	60.1	34.3	53.0	29.3
Total Fuel (excluding Stop)(ml)	584.6	624.7	629.3	586.4	655.8	580.8	589.4	717.8	673.4
Total Fuel (including Stop)(ml)	606.1	652.1	680.3	613.9	700.9	640.9	623.7	770.8	702.7
Total Distance (km)	3.846	3.845	3.851	3.848	3.848	3.850	3.848	3.848	3.847
Fuel Consumption (ml/sec)	1.51	1.65	1.05	1.13	0.93	0.91	0.98	0.87	0.99
Fuel Economy (km/litre)	6.35	5.90	5.66	6.27	5.49	6.01	6.17	4.99	5.48

6. VEHICLE PARAMETERS

After all of the tests had done, data from each tests have been analyzed. The types of analyses were different. From the simple one such as to find the idle fuel consumption of the test vehicle to the regression analysis used in steady speed and urban data. In urban driving data as suggested by BOWYER *et al* (1985), the urban driving data must be aggregated and do a several regression analysis performed.

6.1 Idle Fuel Consumption (α)

The idle fuel consumption was found 0.18 ml/sec ± 0.00 ml/sec. The idle fuel consumption can be changed in the vehicle. It depends on the engine speed controller (idling controller) on the top of the engine. The change of this controller made differences to idling fuel consumption. The idling fuel consumption may vary for same type of same vehicle.

Because of no engine speed indicator in the vehicle, it is very useful to use the engine speed indicator to make sure that the engine speed is same when the test of idling fuel consumption begun. As the result shows the idle fuel consumption were no different, the engine speed during the test assumes was same.

6.2 Drag Fuel Consumption Component (c_1 and c_2)

The parameter of c_1 and c_2 is found from the steady-speed fuel consumption test. When the vehicle travel at steady speed (acceleration and deceleration is zero), the fuel consumption of the vehicle is needed to maintain engine operation, to produce energy against rolling resistance and aerodynamic resistance. Equation 10 described this relationship.

The relationship between fuel consumption (ml/s) and steady speed (m/s) can be shown in Figure 4. The data used in this figure are from steady speed data (9 data) and idling fuel consumption data (one data when speed is zero). This figure describes the fuel consumption increase with the speed increase.

Figure 4 also shows a plot of Equation 10 using BOWYER default values. From Figure 4, the idling value (the average logger speed is zero) does not fall below the value expected from the steady speed result. When the speed higher than 15 m/s (or about 50 km/h), the aerodynamic resistance will become a main factor influenced fuel consumption.

Figure 4 also shows when the speed is higher than 15 m/sec, the fuel consumption for the tollway is higher than BOWYER's curve. This could be due to poor aerodynamics of the test vehicle (Toyota Kijang). This situation will influence the value of c_2. The aerodynamic resistance will increase the fuel consumption of the test vehicle.

The line in Figure 4 used default values of c_1 and c_2 suggested by BOWYER *et al* (1985). These value are 0.03 ml/m and 0.0000972 (ml/m)/(m/s)^2 which can be found in Table 1.

To find the appropriate value of c_1 and c_2, the regression analysis has been conducted as suggested by BOWYER *et al* (1985) with the data from Figure 4. The regression analysis has been done with constant fixed to α.

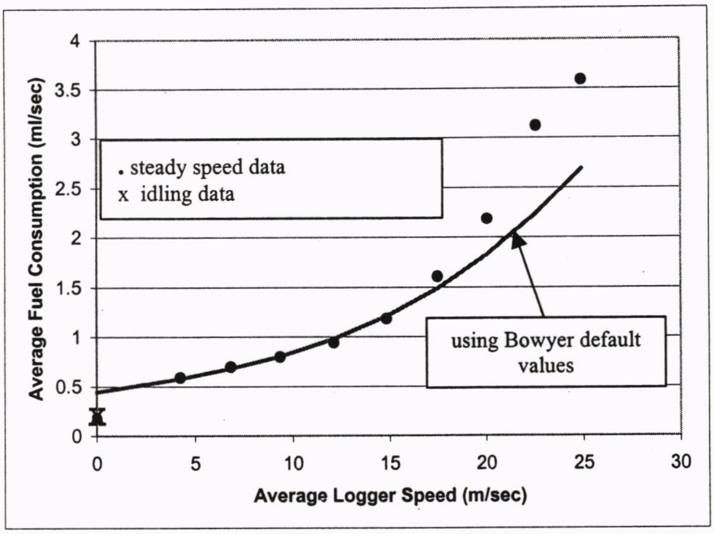


Figure 4. Default Value Line and Steady Speed Data

The regression analysis using the Microsoft Excel version 97 Regression Tools and gave the value of c_1 = 0.043 ml/m and c_2 = 0.000153 $(ml/m)/(m/s)^2$. This regression gave R^2 = 0.98. The value of $R^2 = 0.98$ means that 98% of the variation in fuel consumption is explained by the variation in the values of c_1 and c_2. The F ratio surpasses the critical value at level of confident 95%. The two parameters of the steady-speed fuel consumption model have t value greater than 1.860 (critical value of t test).

6.3 Energy Efficiency of Fuel Consumption (β_1 and β_2)

The values of β_1 and β_2 have been analised from the urban cycle data after the value of α, c_1 and c_2 found. The regression has been conducted to find the value of parameter β_1 and β_2. Every vehicle has its own values of β_1 and β_2. As explained, β_1 is efficiency parameter relating fuel consumption to energy provided by the engine. Small value of β_1 indicates high efficiency of the engine. β_2 is efficiency parameter relating fuel consumption to the product of inertia energy and positive acceleration. Small value of β_2 indicates high efficiency. This analysis is aim to find the representative value β_1 and β_2 for the test vehicle.

6.3.1 Aggregation of Urban Fuel Consumption Data

Fuel consumption cannot be measured accurately over small time interval using flow meter. The fuel flow recorded by the meter is the flow, which goes into the carburetor, and there is a variable time lag between this and the fuel used by the engine to provide force. It is therefore necessary to aggregate the data into reasonably long time intervals. An aggregation interval of between 10 and 20 seconds is recommended by BOWYER *et al* (1985).

To determine β_1 and β_2 with data divided into time intervals, each consisting of a certain number of data points, firstly calculate for each data point the inertial terms:

$$P_{IG} = (Mav + 9.81Mv(G/100))/1000 \tag{11}$$

$$aP_I = Ma^2v/1000 \tag{12}$$

The inertia term of P_{IG} is $P_{(I+G)}$ where:

$$P_I = R_I \times v \tag{13}$$

and

$$P_G = R_G \times v \tag{14}$$

where:

P_I = inertia power in kW.

R_I = inertia force (Ma/1000) in kN, (M= vehicle mass in kg, a= acceleration in m/s2)

R_G = grade force (9.81M(G/100)/1000) in kN, (M= vehicle mass in kg, G= gradient in percent).

v = speed in m/s.

Since the G=0 (assumed that the terrain is level) the P_{IG} becomes P_I and the Equation 11 becomes:

$$P_I = Mav/1000 \tag{15}$$

The Equation 12 is from a x P_I. This Equation is a variable for the third term of Instantaneous Fuel Consumption Model (Equation 7) where the constant is β_2. All of variables from Equation 11 and 15 are given from urban fuel consumption data. The next step is aggregate each of these terms, as well the inertia component of fuel consumption (difference between total and steady-speed fuel consumption) into the time intervals as follows:

$$F_I^{(k)} = \sum \left(f_t - f'_{c,t}\right) \tag{16}$$

$$\begin{gathered} P_{IG}^{(k)} = \sum P_{IG} \\ P_T > 0 \end{gathered} \tag{17}$$

$$\begin{gathered} aP_I^{(k)} = \sum aP_I \\ P_T > 0 \\ a > 0 \end{gathered} \tag{18}$$

where the summation are over the points in time interval number k subject, in some cases, to additional restrictions on P_T and a.

The value of P_T is found from the Equation 19.

$$P_T = P_{IG} + c_1 v / \beta_1^{(0)} + c_2 v^3 / \beta_1^{(0)} \tag{19}$$

Where $\beta_1^{(0)}$ is a first guess of β_1 (could use default value of β_1).

6.3.2 Regression Analysis of Urban Fuel Consumption Data

The aggregation of the urban driving data produces 623 data in 10 seconds interval. The regression analysis has been conducted to the aggregation data of P_I, and aP_I on F_I through the origin, or intercept fixed to zero.

The regression equation can be expressed as:

$$F_I^{(10)} = \beta_1 P_I^{(10)} + \beta_2 a P_I^{(10)} \tag{20}$$

where:

$F_I^{(10)}$ = summation of inertia fuel consumption over 10 seconds (ml/sec)

$P_I^{(10)}$ = summation of inertia power over 10 seconds (kW)

$aP_I^{(10)}$ = summation of inertia power and acceleration over 10 seconds (kW(m/sec^2))

Using Microsoft Excel 97 Regression Tools, The result of regression of P_{IG}, and aP_I on F_I produced $\beta_1 = 0.297$ (ml/kJ) and $\beta_2 = 0.254$ (ml/kJ.m/s^2). The statistical parameter for this regression are $R^2 = 0.54$ and standard error of estimation = 4.39 ml/sec.

The F ratio surpasses the critical value at level of confident 95%. The two parameters of the steady-speed fuel consumption model have t value greater than 1.645 (critical value of t test). The value of $R^2 = 0.54$ means that 54% of the variation in fuel consumption per unit time is explained by the variation in the values of β_1 and β_2 and 46% of the variation in fuel consumption per unit time is accounted for by factors other than β_1 and β_2 i.e. driver behaviour, etc.
The value of standard error of estimation is high, about 4.39 ml/sec. It means that in every second, the estimation of fuel consumption is ± 4.39 ml. This value is high compare to idling fuel consumption.

7. MODEL VALIDATION

Since all the parameter values found in this analysis, for the comparison, this value has been compared with the BOWYER value as shows in Table 6.

Table 6. Comparison of Model Parameter

Parameter	Finding From This Study	Minimum Value *)	Maximum Value *)	Default Value *)
M (kg)	1663	600	2000	1200
α (ml/s)	0.18	0.1	1.0	0.444
c_1 (ml/m)	0.043	0.005	0.112	0.030
c_2 (ml/m)/(m/s)^2	0.0001528	0.0000150	0.0002400	0.0000972
β_1 (ml/kJ)	0.297	0.05	0.16	0.090
β_2 (ml/kJ.m/s^2)	0.253	0.01	0.06	0.045
$b_1 = \beta_1/c_1$ (kN)	0.23	0.10	0.70	0.333
$b_2 = \beta_1/c_2$ (kN/(m/s^2))	0.00051	0.0003	0.0015	0.00108

*) BOWYER *et al* (1985)

All of the parameter is in the range of minimum and maximum value from BOWYER *et al* (1985) except β_1 and β_2. The value of β_1 is higher than maximum value suggested by BOWYER *et al* (1985). This value indicates low efficiency of the engine for producing energy. This can be assumed that the vehicle has a low efficiency in producing energy. The value of β_2 is also higher than maximum value suggested by BOWYER *et al* (1985). This value indicates low efficiency of the engine for producing inertia energy and positive acceleration.

The instantaneous fuel consumption per unit time (ml/sec) can be expressed as:

$$f_t = \frac{dF}{dt} = 0.18 + 0.297 R_T v + \left[0.253 a^2 v\right]_{a>0} \quad \text{for } R_T > 0 \qquad (21)$$

$$f_t = 0.18 \quad \text{for } R_T \leq 0$$

$$R_T = 0.145 + 0.00051 v^2 + 1.663 a + 0.163 G \qquad (22)$$

where:
v = speed in m/sec
a = acceleration in m/sec^2

After all the parameters found and the model has been calibrated, the next step is to estimate the fuel consumption during the urban driving. The total fuel consumption for nine urban data is 6,011.8 ml. With the Equation 21 and 22 the estimated of total fuel consumption during urban driving was 8,010.9 ml. The estimation error is about 33.3% over estimate.

The over estimate value can be explained as follow:

1. The accuracy of c_1 and c_2. The high values of standard error of estimation found from steady-speed fuel consumption model can influence the accuracy of instantaneous fuel consumption.
2. The value of β_1 and β_2 from regression analysis is higher because the assumption of the gradient equals zero. From Equation 11, when $P_{IG} = P_I + P_G$ and assumed that $P_G = 0$, the value of P_I is lower than P_{IG}. Therefore, the variable β_1 becomes higher when the other values constant. This can be affecting the estimation of the model.
3. The Equation 12 is the inertia fuel consumption that found from differences between fuel consumption total and steady speed. The steady speed fuel consumption is calculated when acceleration equals zero or the vehicle traveled in constant speed. From the urban driving data, only 30% data recorded vehicle traveled at a=0. In fact, the steady speed in urban is infrequent especially when time interval divided in second. This can be affected that the value of F_I become higher, so value of β_1 and β_2 become higher too after the regression analysis done.
4. The fuel consumption data from urban driving was collected in 10 seconds time interval. When calculating F_I from Equation 16, the value of f_t (ml/sec) is an average of 10 seconds interval data on the other hand f'_{ct} was calculated using second by second vehicle speed. The accuracy of F_I can be influenced when calculated differences between f_t and f'_{ct}.

8. CONCLUTIONS AND RECOMENDATIONS

The vehicle parameters, which found from this research, can also describe how efficient the test vehicles. The efficiency of the test vehicle can be found in α, c_1, c_2, β_1 and β_2. The different vehicle parameters were found because of the differences in mass-power ratio, aerodynamic resistance and engine efficiency.

The engine efficiency was found very poor for the test vehicle. This is occurred because of the poor engine maintenance of the test vehicle. Using good condition and standard vehicle for collected data is very important to eliminate other factors like poor engine efficiency, poor fuel economy, etc.

This research only considers one vehicle test and gives the representative parameter for this vehicle. This parameter may be vary to other vehicle i.e. engine capacity, mass etc. It is recommended to find parameter values for other vehicles. The range of parameter value of different vehicles can be used to found the representative values for car in Bandung.

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REFERENCES

AKÇELIK, R. (1983), **On The Elemental Model of Fuel Consumption**, Australian Road Research Board, Research Report, ARR No. 124.

BEIN, P. (1993), **VOC Model Needs of A Highways Department**, **Vol. 2,** No. 2, Road and Transport Research.

BIGGS, D.C. (1988), **ARFCOM-Models for Estimating Light To Heavy Vehicle Fuel Consumption**, ARRB Research Report, ARR No.152.

BOWYER, D.P., AKÇELIK, R. and BIGGS, D.C. (1985), **Guide to Fuel Consumption Analyses for Urban Traffic Management**, Australian Road Research Board, Australia.

EVERALL, P.F. (1968), **The Effect of Road and Traffic Conditions on Fuel Consumption**, TRRL Report LR 266.

KENT., J., TOMLIN, J.A. and POST, K. (1982), **Fuel Consumption Modeling in Traffic Links**, Charles Kolling Research Lab. Tech. Note ER-38, University of Sidney.

PRAHARA, EDUARDI (1998), **Development of Instantaneous Car Fuel Consumption Model**, Thesis S2, Program Sistem dan Teknik Jalan Raya (STJR), Pascasarjana Insititut Teknologi Bandung.

SAYERS, M.W., T.D. GILLESPIE and W.D.O. Paterson, (1986), **Guidelines for Conducting and Calibrating Road Roughness Measurements**, Technical Paper No. 46, World Bank, Washington D.C.

WATSON, H.C. (1981), **Calibration and Application of Two Fuel Consumption Models**, Dept. Mech. Eng., Univ. Melbourne, Rep. T 50/81.