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A discussion on the paper on fuel consumption modelling by Post *et al.*

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REFERENCE:

NOTE:

This paper is related to the intersection analysis methodology used in the SIDRA INTERSECTION software. Since the publication of this paper, many related aspects of the traffic model have been further developed in later versions of SIDRA INTERSECTION. Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further research.

A DISCUSSION ON THE PAPER ON FUEL CONSUMPTION MODELING BY POST *ET AL.*

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Post, Kent, Tomlin and Carruthers (1984) described a fuel consumption model based on the instantaneous power demand experienced by a vehicle. Furthermore, they developed a trip-averaged power-demand model and an elemental model as more aggregate models. They compared these two models and a simple average trip speed model of fuel consumption in terms of their prediction abilities using on-road data collected in Sydney. The aim of this discussion is to inform the readers about further work on these models carried out at the Australian Road Research Board with funding from the National Energy Research Development and Demonstration Council. As a result of this work, an extended power-based model was developed, and other models of fuel consumption, including a new elemental model, were derived from it. These models will be briefly discussed and a critical review of the work of Post *et al.* in comparing different aggregate models will be presented in this discussion note.

The starting point of Post *et al.* is an attractive power-based instantaneous model of fuel consumption. At the time of our audit work (Bowyer, Akcelik, Bayley and Biggs, 1982), the reported validation of the model for estimating on-road fuel consumption was found inadequate. The model was only tested for long trips and the estimated fuel consumption was found to be within 3% of the measured fuel consumption (see Table 3 of Post *et al.*). However, a simple travel time model based on this data predicts fuel consumption to within 5% of the measured value. It was not clear for which applications the model was suitable and the errors in predicted fuel consumption were not well documented.

The power model can be considered a basic model in the hierarchy of fuel consumption models (Akcelik, Bayley, Bowyer and Biggs, 1983) and requires instantaneous (second-by-second) velocity, acceleration and grade data. The model provides estimates of instantaneous fuel consumption, but it was not claimed to be accurate at this level and the reported on-road validation was based on long trips as discussed above. If the power model were validated for specific driving manoeuvres such as accelerations, decelerations and steady-speed driving, it could then be used to predict instantaneous fuel consumption in microscopic traffic simulation models, or to derive higher level models of more direct use to the traffic engineer (Akcelik, 1983).

A thorough investigation of the procedures used by Post *et al.* to calibrate the power model is described and alternative procedures are suggested in Biggs and Akcelik (1984). This validation work was undertaken using on-road and dynameter data collected by Post *et al.* as well as new acceleration, deceleration and steady-speed data collected specifically for the validation task. It was found that the model is sufficiently accurate for predicting fuel consumption during trips and sections of trips of 60 seconds or more, and for predicting steady-speed and acceleration fuel consumption, except hard accelerations. The errors were generally less than 10% for these applications.

Further investigations are reported in Biggs and Akcelik (1985). A modified/extended version of the power model is described which considerably improves the model accuracy, especially during hard accelerations. The original model put forward by Post *et al.* has the property that the fuel consumption component associated with inertial power during an acceleration is independent of the acceleration rate. This deficiency is overcome in the extended model by using an acceleration-inertia power term in addition to the total power term. The

model can, in fact, be expressed as an "energy-related" model

$$dF = \alpha dt + \beta_1 R_T dx + [\beta_2 a R_I dx]_{a>0} \quad \text{for } R_T > 0,$$
$$= \alpha dt \qquad\qquad\qquad\qquad \text{for } R_T \leq 0,$$

(1)

where

dF = increment of fuel consumed (mL) during travel along distance dx (m) and in time dt (s),
α = constant idle fuel rate (mL/s), which applies during all modes of driving (as an estimate of fuel used to maintain engine operation),
β_1 = the efficiency parameter which relates fuel consumed to the energy provided by the engine, that is fuel consumption per unit of energy (mL/kJ),
β_2 = the efficiency parameter which relates fuel consumed during positive acceleration to the product of inertia energy and acceleration, that is fuel consumption per unit of energy-acceleration (mL/(kJ·m/s²)),
a = instantaneous acceleration (dv/dt) in m/s², which has a negative value for slowing down,
R_T = total "tractive" force required to drive the vehicle, which is the sum of drag force (R_D), inertia force (R_I) and grade force (R_G) in kN (kilonewtons):

$$R_T = R_D + R_I + R_G.$$

(2)

The resistive forces can be expressed as

$$R_D = b_1 + b_2 v^2,$$

(3)

$$R_I = Ma/1000,$$

(4)

$$R_G = 9.81 M (G/100)/1000,$$

(5)

where

v = speed (dx/dt) in m/s,
G = percent grade that has a negative value for downhill grade,
M = vehicle mass in kg, including occupants and any other load, and
b_1, b_2 = parameters in the drag force function, which relate to rolling, aerodynamic and engine drag.

Note that eqn (1) can be converted to a power-based model by putting f (mL/s) = dF/dt and $P_T = R_T v$ (total power) and $aP_I = aR_I v$ (acceleration-inertia power). It is seen that the extended model uses two efficiency parameters (β_1 and β_2) rather that one (β) used in the model by Post *et al.* For the Melbourne University test car (4.1L Ford Cortina station-wagon with automatic transmission), the following parameter values were found: M = 1680 kg, α = 0.666 mL/s, b_1 = 0.527 kW(m/s)$^{-1}$, b_2 = 0.000948 kW(m/s)$^{-3}$, β_1 = 0.0717 mL/kJ and β_2 = 0.0344 mL/(kJ·m/s²).

A further difference from the original model is that the drag function [eqn (3)] is derived using steady-speed fuel consumption data rather than data collected during coast-down in neutral. The drag forces predicted in this way are similar to those experienced by the vehicle while coasting-down in gear. Thus, engine drag in actual driving is accounted for (there is about 40% difference between the drag power in and out of gear). It has also been found that a two-term drag function is almost as good as a three-term function in terms of overall prediction. However, the two-term function is more attractive analytically due to multicollinearity in the regression estimation of the coefficients of v, v^2 and v^3 in the three-term function.

The estimation accuracy of the new model over acceleration, short cruise and deceleration cycles was found to be very good with mean errors less than 4% of total fuel consumption. The variation in the errors was also found to be relatively small, the standard deviation of the errors ranging from 1–8% of total fuel consumption.

In Biggs and Akcelik (1985), the development of fuel consumption models of four levels of detail within the framework of a modeling hierarchy is discussed. These are:

(a) an energy-related instantaneous model (described above),
(b) a four-mode (acceleration, cruise, deceleration, idle) elemental model,
(c) a running speed model, and
(d) an average travel speed model.

Within the modeling framework, a simpler model is derived from a more detailed 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. A summary of the resulting models for estimation of fuel consumption is given in a guide to fuel consumption analysis in urban traffic management (Bowyer, Akcelik and Biggs, 1984).

Similarly, Post et al. (1984) have derived three different models from their instantaneous power model. The model that predicts fuel consumption as a function of link (or trip) averaged total power (ZTOT) uses PIP as the positive inertial power term. This model gives a comparable accuracy to the PKE (positive kinetic energy) model (e.g. see Watson, Milkins, Preston, Chittleborough and Alimoridian, 1983) which Post et al. have unfortunately neglected in their comparison. The running speed model developed at ARRB is similar to the link-averaged power-demand model in using a PIP/PKE type term and allowing for vehicle parameters explicitly. However, it predicts the drag and stopped delay components of fuel consumption better as it is based on the average running time rather than the total link travel time (the latter includes stopped times).

The elemental model developed by Post et al. appears to have deficiencies in its setup and calibration. Firstly, the stops are defined on the basis of a deceleration to, and acceleration from a speed of 5 km/h (although this point is not clearly stated). The use of a single-speed definition of stops usually results in underestimation of fuel consumption since major slowdowns are not accounted for, e.g. a deceleration from 80 km/h to 10 km/h and subsequent acceleration from 10 km/h to 80 km/h would be entirely neglected. Thus, eqns (18) and (20) of their paper for calculating the cruise time and fuel consumption due to stops would be expected to produce poor estimates in many cases as they depend on the number of stops.

Second, the problem of negative cruise times could be avoided by setting the cruise time to zero and adjusting the acceleration and deceleration times accordingly. The use of distance rather than time as a basis for calculations is a better method. According to this method, acceleration and deceleration distances can be predicted, and cruise distance calculated by subtracting these values from the known section (link) distance.

Furthermore, the use of a function that predicts total power demand for an acceleration or a deceleration as a function of speed only [eqns (9) and (12)] may not have been the best method to use. The alternative approach of integrating the individual terms of the instantaneous power/energy model over typical acceleration and deceleration profiles can allow for different profiles and the effect of gradient, and all vehicle parameters can be kept as explicit parameters (see the four-mode elemental model in Bowyer et al., 1984).

It should also be noted that, when comparing the accuracy of the models, grade and detailed speed profile information (minimum and maximum speeds) were not used in the elemental model calculations whereas they were used in the link-averaged power demand model developed by Post et al.

Poor calibration of the elemental model is best illustrated by the fact that it performs worse than a simple travel speed model! (see Table 7 of Post et al.). A simple regression model that has the number of stops in addition to the average speed as a variable would perform better than the simple average speed model. It is therefore easy to see that the effects of stops are poorly specified in the elemental model described by Post et al.

The suggestion by Post et al. that "there is little to recommend the use of the elemental model" may apply to the elemental model developed by Post et al., but not necessarily to other elemental models. Various elemental models have been successfully used in traffic engineering applications (e.g. see Robertson, Lucas and Baker, 1980; Luk and Akcelik, 1984).

The newly developed four-mode elemental model (Biggs and Akcelik, 1985; Bowyer et

al., 1984) has none of the shortcomings of the elemental model considered by Post *et al.*, and has all the advantages of the power-demand model: explicit use of vehicle parameters, use for emission modeling, etc. Analysis of errors reported in Biggs and Akcelik (1985), in fact, shows that R^2 values of around 0.98 can be obtained for this elemental model over idle–acceleration–cruise–deceleration cycles (using Sydney on-road data collected by Post *et al.*). Comparison of estimates from the four-mode elemental model with the estimates from a "running speed" model, which is similar to the Post *et al.* link-averaged power-demand model, shows that the four-mode elemental model produces better results where detailed traffic information is not available.

The most contentious statement in the paper by Post *et al.* is the conclusion that the elemental model should not be considered for use in practice, since it produces worse predictions than the simple travel speed model. The judgment is based on overall prediction ability, not on ability to predict the effects of changes in fuel consumption components. For example, traffic engineers/managers are often interested in finding out the marginal effects of delay and number of stops in traffic control systems. In this context, a model which is slightly inferior in terms overall prediction of fuel consumption may be more useful (for design/optimisation purposes) because it can help predict the effects of different control/design options on different traffic variables (performance measures). The link averaged power-demand model as expressed by eqn (25) of Post *et al.* is not particularly useful according to this criterion; for example, it cannot pass the simple test of predicting the effect of a change in stopped delay time on fuel consumption correctly as shown in the example below.

As shown in Fig. 1, three trips along the same road section ($X = 1$ km) are considered, which have identical acceleration–cruise–deceleration patterns but different idling times, d_s (hence different average speeds, $\bar{v}$). The discussion below applies independent of acceleration and deceleration profiles provided they are identical for each trip. In this example, acceleration and deceleration times are equal ($t_a = t_d = 10$ s) and the cruise time, $t_c = 50$ s for all trips. Thus, the running time, $t_r = t_a + t_c + t_d = 70$ s is constant. However, the stopped (idling) times are $d_s = 10$, 50 and 170 s for Trips A, B and C, respectively. The corresponding "interrupted" travel times ($T = t_r + d_s$) are 80, 120 and 240 s, and the average interrupted speeds ($\bar{v} = 3600 \, X/T$) are 45, 30 and 15 km/h, respectively. PIP values are calculated from
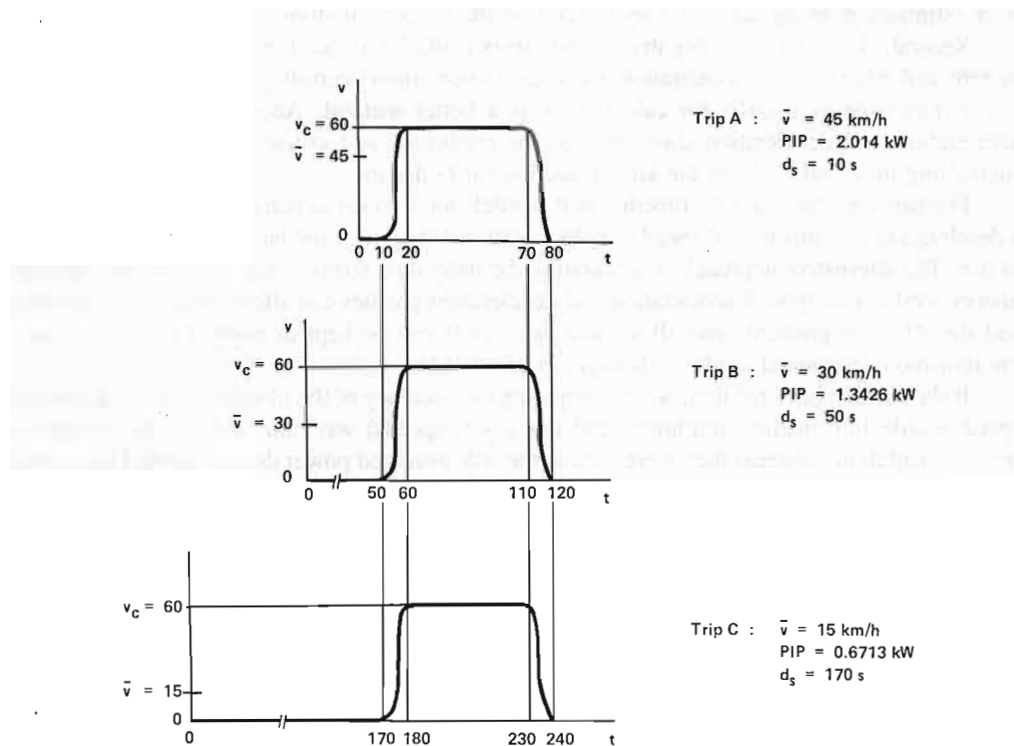

Fig. 1. Three trips with identical acceleration–cruise–deceleration patterns but different idling times: An example to show a deficiency of the link-averaged power demand model.

eqn (24) of Post *et al.* using $v_2 = 60$, $v_1 = 0$, $M = 1160$ kg and $T = 80$, 120 and 240 s, and PIP = 2.014, 1.3426 and 0.6713 kW are found for Trips A, B and C, respectively.

The following fuel consumption values are predicted by the PIP $- \bar{v}$ model [eqn (25) of Post *et al.*] using the above data:

$$\text{Trip A:} \quad F_A = 96.9,$$

$$\text{Trip B:} \quad F_B = 105.8,$$

$$\text{Trip C:} \quad F_C = 153.8.$$

The difference between fuel consumptions for Trips B and A is $\Delta F_{BA} = 8.9$ mL and for Trips C and A is $\Delta F_{CA} = 56.9$ mL. The only differences between these trips are due to the idling times: $\Delta d_{sBA} = 40$ s and $\Delta d_{sCA} = 160$ s. Because the idling fuel consumption rate is known, the expected values of ΔF_{BA} and ΔF_{CA} can be calculated directly in the elemental model fashion. Since the idling fuel consumption rate is $\alpha = 27.5/60 = 0.4583$ mL/s, $\Delta F_{BA} = 0.4583 \times 40 = 18.3$ mL and $\Delta F_{CA} = 0.4583 \times 160 = 73.3$ mL are found. The corresponding errors in the predictions of the link-averaged power demand model are 51% and 22%, respectively.

For a similar example and detailed discussion on the need for an *elemental* model for traffic design/optimation purposes, the reader is referred to Akcelik (1983) and Bowyer *et al.* (1982).

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