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REPRINT

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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 Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further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.

EFFICIENCY AND DRAG IN THE POWER-BASED MODEL OF FUEL CONSUMPTION

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Abstract—The efficiency and drag parameters in the instantaneous fuel consumption model are explained by comparing the model with the original power-based model developed at Sydney University, and relating the two models to a conceptual model. Various efficiency factors internal to the vehicle system can be modelled as contributing to the efficiency parameter, or explicitly as power components. The single efficiency parameter in the *original* power model includes engine drag and all other internal inefficiency components of the vehicle system. On the other hand, the two efficiency parameters in the Australian Road Research Board (ARRB) model have been derived in such a way that they do not include the engine/internal drag in the steady-state driving mode. A fuel consumption model that uses a drag force component measured by coast-down (in neutral) should employ a *nonconstant efficiency factor* (i.e. a factor dependent on speed and acceleration rates). Otherwise, a satisfactory level of accuracy cannot be achieved, particularly if the prediction of fuel consumption during different modes of driving is required. If all power terms are modelled explicitly, then a basic (constant) engine efficiency parameter can be employed. The basic efficiency factors found from engine maps are of the order of 0.06 to 0.08, which are very close to the values obtained for the ARRB model. This confirms the accuracy of the calibration method used for the ARRB model.

INTRODUCTION

The purpose of this paper is to explain the efficiency and drag parameters in the Australian Road Research Board (ARRB) instantaneous fuel consumption model (Biggs and Akcelik, 1984, 1985, 1986; Bowyer, Akcelik, and Biggs, 1985) in response to a discussion by Fisk (1989).

The ARRB model was developed from a model originally proposed by researchers at Sydney University (Post *et al.*, 1981, Kent, Post, and Tomkin, 1982). Both the Sydney University and the ARRB models can be referred to as power, or energy, models of fuel consumption. For simplicity, this paper will be presented in terms of *power*, without the corresponding *energy* formulations. The Sydney University model will be referred to as the *original model*. The issues raised by Fisk can be clarified by comparing the ARRB model with the original model.

The models that express fuel consumption as a function of power requirements use an efficiency parameter, β, that relates fuel to power. The precise meaning of β in a given model depends on how that model is derived and calibrated. Essentially, β allows for engine efficiency as well as the efficiencies of other internal vehicle factors. Various *efficiency factors* internal to the vehicle system can be modelled as contributing to the β parameter, or explicitly as power components. Much of the discussion in the paper by Fisk relates to the question of modelling engine/internal drag power *explicitly as a power component*, or allowing for it *implicitly in the β parameter*.

It is shown in the following discussion that the efficiency parameter in the original power model includes engine drag and all other internal inefficiency components of the vehicle system (except a portion of transmission drag, which is accounted for in the coast-down drag). On the other hand, contrary to the assertion of model misspecification by Fisk, the efficiency parameters in the ARRB model have been derived in such a way that they do not include the engine/internal drag in the steady-state driving mode. Importantly, the β parameter in the original model is an *average* efficiency factor that relates to all driving modes, whereas the ARRB model allows for different efficiencies in different driving modes, particularly in the steady-speed (constant-speed) driving and positive acceleration modes.

In terms of *overall accuracy*, the use of engine/internal drag power explicitly or as part of the efficiency parameter may not be very important. However, an important advantage of the power/energy-based fule consumption models is the ability to *explain* the vehicle, road, and traffic factors that affect fuel consumption. In addition, the ARRB model endeavours to produce accurate estimates of fuel consumption in different *driving modes* in an elemental fashion since this is essential for the model to be useful for urban traffic management purposes (Akcelik, 1983). The ability to explain the factors contributing to fuel consumption in individual driving modes is a particular advantage of the model. It is therefore important that correct meanings are given to model parameters. The discussion by Fisk is useful for this reason.

For simplicity, the formulations in this paper are presented for the case of a level road (no grade effects) and for positive power requirements.

THE ORIGINAL POWER MODEL

The original power model (Post *et al.*, 1981, Kent *et al.*, 1982) expresses the instantaneous fuel consumption as

$$f_t = \alpha + \beta P_T, \tag{1}$$

where

f_t = instantaneous fuel consumption rate (mL/s),
α = idle fuel consumption rate (mL/s),
β = an average efficiency factor (mL/s/kW, or mL/kJ), and
P_T = total power required (kW).

In the original model, the total power required (P_T) is expressed as the sum of the *coast-down* drag power (P_D) and the inertia power (P_I), and is qualified as the *instantaneous power output of the vehicle*. The drag power is measured from coast-down tests with the gear in neutral, and as such it includes the rolling and air resistances as well as a component of the driveline drag (internal resistance forces from the wheels to the output of the gear box). Thus, the total power in the original model is

$$P_T = P_D + P_I = (R_D + R_I)v = (R_{RA} + R_B + R_I)v, \quad (2)$$

where

v = vehicle speed (m/s),
R_D = total drag force ($= R_{RA} + R_B$),
R_{RA} = sum of rolling and air resistances,
R_B = driveline drag, and
R_I = inertia force ($= ma$ where m is the vehicle mass and a is the acceleration rate) with all forces in units of newtons (N).

The drag (force) from coast-down tests is of the form (Biggs and Akcelik, 1984, 1985);

$$R_D = d_1 + d_2v^2, \quad (3)$$

where d_1 and d_2 are derived by regression using coast-down data. Therefore, d_1 and d_2 in eqn (3) cannot be easily equated with mgc_r and $0.5\rho Ac_a$ in the well-known equation given by Fisk (unnumbered), due to the problems of multicollinearity. Furthermore, the driveline drag, R_B, needs to be considered as part of the rolling resistance coefficient c_r. Thus, d_1 and d_2 can be taken *only as roughly* equal to the rolling and air resistances. This is one of the considerations that influenced our decision not to include explicit expressions for rolling resistance and air drag in the ARRB model.

Thus, the original power model can be expressed as

$$f_t = \alpha + \beta(P_D + P_I) \quad (4)$$

or

$$f_t = \alpha + \beta(R_D + R_I)v \quad (4a)$$

or

$$f_t = \alpha + \beta(d_1 + d_2v^2 + ma)v. \quad (4b)$$

For this model, β is derived by regression of ($P_D + P_I$) on ($f_t - \alpha$) through the origin using instantaneous data points *for all driving conditions* (constant-speed, acceleration, etc.)

It should be noted that parameter β in eqns (1) and (4) is different from β_1 and β_2 in the ARRB model, whereas Fisk uses β_1 for both the original model and the ARRB model [see Fisk's eqns (3 and 4)]. To explain that β_1 in the ARRB model and β in the original model are *not* the same efficiency parameter, a conceptual model that uses different efficiencies for the constant-speed and acceleration modes of driving will be discussed in the following section.

The starting point of our development of the ARRB model was a detailed examination of the β parameter in the original power model. Our analyses and findings are explained in detail in Biggs and Akcelik (1984, 1985). In summary, we found that an average β value does not give accurate results since β varies as a function of speed and acceleration rate. As a result of an effort to achieve improved accuracy in predicting fuel consumed during constant-speed driving as well as acceleration manoeuvres, we adopted the use of two efficiency paramters, β_1 and β_2, and allowed for an engine/internal drag component to be part of the total drag power. This is explained below, starting first with a conceptual model.

A CONCEPTUAL MODEL

As a basis for comparing various models, let us now define the following general form of the fuel consumption model:

$$f_t = \alpha + \beta_c P_c + \beta_a P_a, \tag{5}$$

where

$$P_c = P_D + P_{ec} = (R_D + R_{ec})v \tag{6}$$

$$P_a = P_I + P_{ea} = (R_I + R_{ea})v \tag{7}$$

and

P_D, P_I = coast-down drag and inertia powers as defined for eqns (2) to (4),
P_{ec}, P_{ea} = power requirements associated with engine/internal drag during constant-speed driving and acceleration (R_{ec}, R_{ea} = corresponding engine/internal drags),
P_c = total drag power during constant-speed driving,
P_a = total inertia drag power, and
β_c, β_a = efficiency parameters applicable to constant-speed and acceleration modes of driving.

For this conceptual model, assume that β_c and β_a are average engine/internal efficiency factors and consider that P_{ec} and P_{ea} are the power requirements additional to P_D and P_I. Assume that P_{ec} and P_{ea} are associated with power requirements above those at the engine idling (zero vehicle speed) conditions. Thus, P_{ec} and P_{ea} would allow for power to run the engine accessories and overcome engine drag (internal engine friction) as well as transmission losses, excluding the parts that are already allowed for in the idle fuel consumption rate, α, and the coast-down drag, P_D.

COMPARING THE ORIGINAL MODEL WITH THE CONCEPTUAL MODEL

Let us now express the efficiency parameter of the original power model, β in eqn (1), in terms of the efficiency parameters of the conceptual model, β_a and β_c in eqn (5). From eqns (4) to (7):

$$\beta = [\beta_c(P_D + P_{ec}) + \beta_a(P_I + P_{ea})]/(P_D + P_I) \tag{8}$$

or assuming the same efficiency factor for the constant-speed and acceleration modes of driving $\beta_c = \beta_a = \beta_e$,

$$\beta = \beta_e\{1 + [(P_{ec} + P_{ea})/(P_D + P_I)]\}. \tag{9}$$

Thus, the efficiency factor in the original power model is seen to include the engine and other internal vehicle drags. This is only because the total power required, P_T, used in its derivation does not include the power used by the engine to overcome its own and other internal frictions (particularly transmission losses) and to power engine accessories. In other words, fuel used to overcome engine/internal drag and provide power for accessories are modelled as part of the efficiency factor.

Since the original power model of fuel consumption uses β as an *average* (constant) efficiency factor for all modes of driving, its accuracy is limited for predicting fuel consumed in different modes of driving. To show this, let us consider fuel consumed during constant-speed driving. The considerations of drag associated with constant-speed driving and an efficiency parameter derived using constant-speed fuel consumption data help to provide answers for the question under discussion.

DRAG ASSOCIATED WITH CONSTANT-SPEED DRIVING

Concerning the way we derived the ARRB model, Fisk states that "(the model) uses fuel consumption data, taken from constant speed vehicle tests, to determine rolling and aerodynamic resistance coefficients; this is a departure from the usual practice of calibrating the drag model independently of fuel consumption considerations by such procedures as neutral coast-down."

In various reports and papers explaining the development of the ARRB model (Biggs and Akcelik, 1984, 1985, 1986), we clearly distinguished between a drag power function derived from coast-down data [let us denote this by P_D as in eqns (1) to (9)] and a drag power function derived from constant-speed fuel-consumption data (denote this by P'_D). We also distinguished between coast-downs *in-gear* and coast-downs with the gear *in neutral*, and observed that the former method gives a function close to P'_D.

For the Cortina test car (4.1 L, automatic, idle fuel rate $\alpha = 0.666$ mL/s, mass = 1,680 kg) (Biggs and Akcelik, 1985, 1986), we found

$$P_D = 0.269\, v + 0.000672\, v^3, \tag{10}$$

and

$$P'_D = P_D + 0.0171\, v^2, \tag{10a}$$

where P_D is in kW, v is in m/s. The extra term in eqn (10a) is explained as the *engine/internal drag*. However, derivation of the engine/internal drag term depends on the use of the efficiency factor; in other words, the model assumptions come into play. Similarly, the efficiency factor in the original power model depends on the derivation of the coast-down drag power. Our modelling approach uses a basic efficiency factor [e.g. β_e in eqn (9), or more correctly, β_c in eqn (8) as will be discussed further] *that excludes the engine/internal drag component.*

A further observation shows the inadequacy of the coast-down (in neutral) drag power function to represent constant-speed fuel consumption. It was found that constant-speed fuel consumption rates depend on gear (Biggs and Akcelik, 1984, 1986). If the vehicle remains in a lower gear at a given vehicle speed, the engine speed, and therefore the fuel consumption rate, is higher. At a given vehicle speed, the fuel consumption associated with the coast-down (in neutral) drag is a fixed value, and the additional fuel consumption that is different for different gears is explained with the effect of engine/internal drag.

EFFICIENCY FACTOR DERIVED FROM CONSTANT-SPEED DRIVING DATA

Constant-speed fuel consumption in terms of the original power model [eqns (1) to (4)] is

$$f_c = \alpha + \beta' P_D, \tag{11}$$

where β' is an efficiency factor derived using constant-speed fuel consumption data only, and in terms of the conceptual model [eqns (5) to (7)], it is

$$f_c = \alpha + \beta_c(P_D + P_{ec}), \tag{12}$$

where f_c is in mL/s. Putting $P'_D = P_D + P_{ec}$ (constant-speed drag power as the sum of coast-down drag and engine/internal drag), eqn (12) is rewritten as

$$f_c = \alpha + \beta_c P'_D. \tag{12a}$$

For eqn (11), β' is estimated by regression of P_D on $(f_c - \alpha)$, and in terms of eqn (8), this implies

$$\beta' = \beta_c[1 + (P_{ec}/P_D)] = \beta_c P'_D/P_D. \tag{13}$$

For example, we reported in Biggs and Akcelik (1984) that we obtained $\beta = 0.111$ and $\beta' = 0.120$ for the Cortina test car. Because β is affected by acceleration data, it is different from β_c and cannot be used in eqn (13). However, consider P'_D and P_D given by eqns (10) and (10a). From eqn (13),

$$\beta = \beta_c\{1 + [0.0171\ v^2/(0.269\ v + 0.000672\ v^3)]\}, \tag{14}$$

a speed-depedent efficiency factor is found. (Equation (14) can be roughly approximated by

$$\beta' = 0.141 - 0.001\ v. \tag{15}$$

For example, at $v = 80$ km/h ($v = 22.22$ m/s), $\beta' = 0.119$, close to the average value mentioned above. This shows that it is possible to approximate the conceptual model by using a speed-dependent efficiency parameter, while using the coast-down drag power (P_D) in the model. Alternatively, the engine/internal drag, P_{ec}, can be used explicitly (as in the conceptual model) and a basic efficiency parameter β_c can be used as a constant value. Either way, an estimate of P_{ec} is required. For this purpose, the difference between the drag power functions obtained from the coast-down data (in neutral) and constant-speed fuel consumption can be used. In this case, two sets of experiments are needed to calibrate the model. In the ARRB model, we tried to avoid this requirement by using P'_D obtained from constant-speed fuel consumption data that includes engine/internal drag implicitly. This was derived as a two-term function of the form

$$P'_D = b_1 v + b_2 v^3 \tag{16}$$

or

$$R'_D = b_1 + b_2 v^2, \tag{16a}$$

where P'_D is in kW, v is in m/s, and R'_D is in newtons (N).

In contrast with d_1 and d_2 in eqn (3), b_1 and b_2 in eqn (16) include the effects of *engine/internal drag*. This is clearly stated in Bowyer *et al.* (1985) (where notation R_D is used for R'_D of this paper) although our use there of the term *tractive force* to include engine/internal drag may have caused confusion. For the Cortina test car $b_1 = 0.527$ and $b_2 = 0.000948$ were found. Equation (16) with these parameter values give results that are close to the drag power predicted by eqn (10a), which has the engine/internal drag as an explicit term.

One issue remains for discussion: how do we obtain an estimate of β_c (a basic constant efficiency factor) from available data? Only if we know β_c can we construct a model with an explicit P_{ec} term, or with a speed-dependent β factor. To answer this, let us consider the fuel consumed during accelerations.

ACCELERATION FUEL CONSUMPTION CONSIDERATIONS

One of the findings of our early analysis of the original power model (Biggs and Akcelik, 1984) was that estimates of β were very dependent on the *drive cycle* used for the collection of data. This can be explained in terms of eqn (8) in that β is influenced by the speeds and acceleration rates, which determine drag and inertia power values. Another finding was that the original power model underestimated fuel consumption during periods of high power, especially for hard acceleration. *An anomaly of the original power model was that it implied fuel conservation by accelerating as hard as possible.* The dependence of fuel consumption on acceleration rate and acceleration profile is discussed in detail in Biggs and Akcelik (1985) and Akcelik and Biggs (1987).

Early analysis also showed that the efficiency factor derived using the acceleration data is less than the factor based on constant-speed data (see Biggs and Akcelik, 1984, Section 6.3.8 and Table XXI). It was also established that the efficiency factor is dependent on both acceleration rate and speed (if it is conceived and derived as for the original power model of fuel consumption as described above). Applying an average efficiency factor derived using coast-down [β' in eqn (13)] to the acceleration data was found to be inadequate since this method failed to predict differences between slow and hard accelerations.

THE ARRB MODEL OF FUEL CONSUMPTION

The findings summarised above led us to the development of the ARRB model on the basis of the following assumptions:

(i) There is a basic efficiency parameter β_1 that applies to both constant-speed and acceleration modes of driving [$\beta_1 = \beta_c$ in terms of eqn (8)].

(ii) β_1 is less than β of the original model. Using β_1 in association with the drag power based on coast-down (neutral) data, constant-speed fuel consumption is underestimated. The amount of underestimation is due to fuel consumption associated with engine/internal drag [$\beta_c P_{ec}$ in terms of eqns (5) and (13)].

(iii) There is a component of acceleration fuel that is additional to $\beta_1 P_I$. This is expressed as $\beta_2 a P_I$, where β_2 is considered to be a secondary efficiency parameter that relates fuel to the product of inertia power and acceleration rate, aP_I, for positive accelerations ($a > 0$). This allows for the effects of different engine speeds during slow and hard accelerations and a small drop in efficiency at very high power levels.

Based on assumptions (i) to (iii), and in the context of the present paper, the ARRB model can be written as

$$f_t = \alpha + \beta_1 P'_D + \beta_1 P_I + \beta_2 [aP_I]_{a>0}, \tag{17}$$

where $P'_D = P_D + P_{ec}$ is the sum of coast-down drag and engine (and other internal) drag powers.

As reported in detail in Biggs and Akcelik (1985, 1986) and in Bowyer *et al.* (1985), the calibration procedure for the ARRB model is as follows.

(i) Estimate idle rate, α, by measuring total fuel consumed while idling (F_i in mL) over an interval of t_i seconds ($\alpha = F_i/t_i$). Obtain average α from several measurements.

(ii) Using α from (i), estimate parameters c_1 and c_2 in the following function for constant-speed fuel consumption:

$$f_c = \alpha + c_1 v + c_2 v^3, \tag{18}$$

where $(c_1 v + c_2 v^3)$ is equivalent to $\beta_1 P'_D$ in eqn (17); therefore, $c_1 = \beta_1 b_1$ and $c_2 = \beta_2 b_2$ where b_1 and b_2 are the drag power parameters as in eqn (16) (f_c in this paper is equivalent to $f'_{c,t}$ in previous reports). Parameters c_1 and c_2 are estimated by regression of $(f_c - \alpha)$ on v and v^3 (with no constant term).

(iii) Using f_c from (ii), estimate parameters β_1 and β_2 in the following function for the *inertial component* of fuel consumption ($f_a = f_t - f_c$):

$$f_a = \beta_1 P_I + \beta_2 [aP_I]_{a>0}, \tag{19}$$

which is the last two terms of eqn (17). Estimate β_1 and β_2 by regression of f_a on P_I and aP_I (with no constant) using data points for positive acceleration ($a > 0$) only.

(iv) Estimate b_1 and b_2 from

$$b_1 = c_1/\beta_1 \quad \text{and} \quad b_2 = c_2/\beta_1. \tag{20}$$

It is seen that β_1 and β_2 are derived using *only the inertial component* of fuel consumed during the acceleration mode of driving. Thus, the constant-speed fuel consumption component (f_c) does not come into the derivation of β_1 and β_2, and therefore β_1 is not expected to include the engine/internal drag associated with constant-speed driving (although cross-correlation is expected between β_1 and β_2).

To repeat the explanation given above using the notation of Fisk, our procedure calibrates β_e by the acceleration tests, and is equivalent to finding

$$\beta_e = (f_t - f_c)/\text{mav}, \tag{21}$$

where $f_c = \alpha + c_1 v + c_2 v^3$ is estimated as in (ii) above. However, β_e from eqn (21) is not quite the same as β_1 in eqn (19). The ARRB model separates total engine/internal drag (F_2) into constant-speed and inertial drag components ($F_2 = F_{2c} + F_{2a}$), and F_{2c} is considered in relation to f_c whereas F_{2a} is considered in relation to f_a. Note that $F_{2a} = (\beta_2/\beta_1)ma^2$ explains the meaning of the β_2 term in the ARRB model as an *extra* inertial drag power term. This extra drag is associated with higher engine speeds (due to lower gears) during acceleration manoeuvres and includes transmission losses as well as rotational inertias (which are accounted for using the *effective mass* concept in more detailed models of fuel consumption).

In conclusion, the ARRB calibration procedure does not conflict with the force equations written by Fisk, and the author disagrees with Fisk about her assertions regarding the meaning and derivation of the efficiency parameters β_1 and β_2 in the ARRB model of fuel consumption.

The best test of the accuracy of calibration method is the accuracy of the resulting fuel consumption model. The accuracy of estimates from the ARRB model for individual driving modes, individual drive cycles, and for longer trips is a good indicator of the soundness of the calibration method (see Biggs and Akcelik, 1985, 1986). In its form given in Bowyer *et al.* (1985), the model cannot predict fuel consumption related to rolling resistance and air resistance explicitly. Although the model could be extended to produce these estimates by incorporating the use of a coast-down drag function into the calibration procedure, it is probably not the best model to predict fuel consumption at this level of detail. Mechanistic vehicle/engine mapping models are more appropriate for this purpose (see Akcelik *et al.* 1983; Biggs, 1987, 1988).

FURTHER CONSIDERATIONS

Considering the conceptual model in eqns (5) to (7), the inertial component of the ARRB model [eqn (19)] can be specified in terms of an *extra inertial* (*engine/internal*) *drag power*, P_{ea}, which includes engine and transmission losses and rotational inertias. Putting $\beta_a = \beta_1$ and $r = \beta_2/\beta_1$ as a constant factor,

$$P_{ea} = [raP_I]_{a>0} \tag{22}$$

can be written. Thus, eqn (19) becomes

$$f_a = f_t - f_c = \beta_1\{P_I + [raP_I] \quad a > 0\}. \tag{23}$$

It should be noted that this is a *new interpretation* proposed here. The original derivation of the $\beta_2 aP_I$ term was arrived at after testing various functions for improved acceleration fuel consumption accuracy with sensitivity to acceleration rates.

Alternatively, inertial fuel consumption could be explained in terms of an *efficiency factor* which is a linear function of the acceleration rate:

$$\beta_a = \beta_1 + [\beta_2 a]_{a>0}. \tag{24}$$

The preferred method is to allow for extra inertial power components explicitly as in eqn (22). Thus, the ARRB model could be expressed as

$$f_t = \alpha + \beta_1 (P_D + P_{ec} + P_I + P_{ea}), \tag{25}$$

where β_1 is a *basic (constant) efficiency factor*, and various power terms are given by

$$P_D = d_1 v + d_2 v^3 \tag{25a}$$

$$P_{ec} = d_3 v^2 \tag{25b}$$

$$P_I = mav \tag{25c}$$

$$P_{ea} = (\beta_2/\beta_1)\, ma^2 v \quad \text{for } a > 0, \tag{25d}$$

where P_D is the coast-down (neutral) drag power, P_I is the inertia power, and P_{ec} and P_{ea} are the extra engine/internal drag powers during constant-speed driving and accelerations. Equations (25) would allow the prediction of fuel consumption associated with rolling and air resistances explicitly (but approximately). For the Cortina test car, the parameters in eqn (25) are

$$\alpha = 0.666 \text{ mL/s}, \quad m = 1680 \text{ kg}$$

$$d_1 = 0.269, \quad d_2 = 0.000672, \quad d_3 = 0.0171$$

$$\beta_1 = 0.072 \text{ and } \beta_2/\beta_1 = 0.472.$$

The model could be taken further in this direction to express the idle fuel rate as $\alpha = \beta_1 P_{ei}$ where P_{ei} is engine drag at zero vehicle speed. Thus, the model could be expressed as

$$f_t = \beta_1 P_T, \tag{26}$$

where the total power, P_T, is given by

$$P_T = P_{ei} + P_D + P_{ec} + P_I + P_{ea}. \tag{26a}$$

In this form, the model is closer to the more basic engine-vehicle mapping models in the hierarchy of fuel consumption models (Akcelik *et al.*, 1983). The latest modelling work at ARRB (particularly for truck fuel consumption modelling) progressed in this direction (Biggs, 1987, 1988). This work used explicit and more detailed functions to estimate rolling, aerodynamic and cornering resistances, engine drag, power for vehicle accessories, idle fuel rate, etc. as a function of various variables including the engine speed (rev/min).

With this type of model where various power terms (lost or used) are modelled explicitly, the engine efficiency parameter approximates to a basic (constant) factor that is a measure of how well the engine converts fuel to power. By analysing engine maps, Biggs (1987), 1988) found expressions for engine efficiency for this type of model. Basic (constant) efficiency factors from engine maps are of the order of 0.06 to 0.08, which are very close to the β_1 values we obtained for the ARRB model, when the effects of drive train losses are removed from β_1. On the other hand, the β parameter estimated for the original power model is about twice the value of the engine efficiency parameter obtained from engine maps. This confirms the accuracy of the calibration method used for the ARRB model. It is found that the efficiency factors from this method are fairly constant for a wide range of cars and trucks.

CONCLUSION

Essentially, Fisk (1989) argues for a fuel consumption model that uses tractive force (or tractive power) as an external force/power with a drag force component that can be measured by coast-down (in neutral) tests. It is shown in this paper that, if such a model is developed by using a *nonconstant efficiency factor* (i.e. a factor dependent on speed and acceleration rates), it would differ from the ARRB model only in form and would be expected to produce similar accuracy. However, if constant efficiency factors are used in association with the drag force/power predicted by coast-down tests (in neutral), a satisfactory level of accuracy cannot be achieved, particularly if the prediction of fuel consumption during different modes of driving is required.

Alternative to the use of efficiency factors that depend on speed and acceleration rate is the use of a basic (constant) efficiency factor that applies to all modes of driving and express various power terms (lost or useful) explicitly. The ARRB model discussed by Fisk uses this approach. The engine/internal drag associated with constant-speed driving can be expressed explicitly, but this would result in additional data requirements for model calibration.

Recent studies at ARRB considering engine maps have firmly confirmed the results of the method of calibration used for the ARRB model. The level of accuracy of the ARRB model was reported in detail previously. Considering that it is still a simplified representation of a complex process (that is, by no means a perfect model), the accuracy of the ARRB model is found satisfactory for its intended use in traffic management/ engineering applications.

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