Evaluation of state-of-the-art VOC models

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ABSTRACT

Determination of vehicle operating costs (VOC) relies on surveys, mechanistic modelling and statistical analysis. Naturally, estimates obtained by models developed from these efforts differ.

This paper discusses the technological, regulatory and economic factors that limit the transferability of previously developed VOC data to current North American conditions. The following models are then reviewed with respect to VOC estimation methodology and transferability: the Texas Research and Development Foundation (TRDF) model, the World Bank’s HDM-III, the Australian ARFCOM and NIMPAC, the Swedish VETO, the British COBA, the NZVOC from New Zealand, and the South African VOC methodology.

Only VETO and ARFCOM stand up to the test, but VETO is not available for a personal computer and ARFCOM is restricted to fuel consumption.
The subject of this paper was initiated in 1990, when the Ministry of Transportation and Highways (MoTH) of British Columbia embarked on an examination of road user cost models for use in appraisals of highway infrastructure investments. Vehicle operating costs (VOC) are a major contribution to user costs. Another paper (Bein 1993) describes VOC model needs identified at MoTH. The present paper evaluates the major VOC models.

In the research on VOC, fuel consumption and speeds can be readily measured by tests. Other variables require rather tedious and long lasting observations under a variety of road conditions. Consequently, determination of the total VOC rely on a mix of survey work, mechanistic modelling and statistical analysis, and the VOC estimates by the models developed from these efforts differ. Furthermore, the VOC models and their estimates are generally not transferable outside the economic, technological, fleet operating and regulatory conditions in which they were developed. The following major models have been evaluated with respect to the suitability of the VOC methodology and its transferability to present North American road infrastructure planning needs:

- the Texas Research and Development Foundation (TRDF) model (Zaniewski et al. 1982),
- the World Bank’s HDM-III (Watanatada et al. 1987),
- the Australian ARFCOM (Biggs 1988) and NIMPAC (National Association of Australian State Road Authorities 1979),
- the Swedish VETO (Hammarström and Karlsson 1987), and
- the British COBA (Great Britain Department of Transport 1989).

New Zealand’s NZVOC model, and South African VOC models draw on one or more of the major models, but they contain original contributions, which are reviewed in this paper as well.

This paper starts with a discussion of the factors which determine a VOC model’s transferability. The main methodological deficiencies of the VOC models are then described, followed by a critique of each of the major VOC models.

TRANSFERABILITY OF RESULTS

The VOC models reviewed in this paper are specific to the time and location of each of the underlying studies. Chesher and Harrison (1987) explain why VOC models are not necessarily transferable to radically different environments. Some additional factors specific to current North American conditions are as follows.

Vehicle technology

Fuel efficiency receives most attention in the context of VOC. Models which claim transferability to conditions other than the experimental ones, only embody fuel efficiency calibration parameters. Changes in vehicle design, manufacture, components and factory warranty policies are as important because they affect vehicle maintenance costs, durability and utilisation which, in turn, determine...
depreciation and interest costs. Together, these VOC components outweigh fuel costs. The future may see new vehicle technology, for example, in North America the RoadRailer in inter-modal haulage, and the Lean Machine on the urban scene. To derive VOC for these vehicles now would be speculation.

**Fuel efficiency**

The following changes in technology have had the greatest effect on fuel consumption: lower mass and aerodynamic drag of cars in the current fleet; configuration and lower tare mass of trucks; widespread use of radial tyres on trucks and trailers; greater use of aerodynamic drag reduction devices on trucks; and, improvements in engine efficiency and lower idle fuel rate. Current vehicle fleets are more energy-efficient. The results of 1974-1982 research in North America to improve fuel efficiency have been implemented as: standard adoption of devices for speed control; air deflection; truck driver monitoring and education; and, generally more efficient components in vehicles. The quest for lower gross weights, better aerodynamics, alternative propulsion systems and fuels will move into the next century as the developed countries will continue to grow more dependent on oil-producing countries (Organization for Economic Co-operation and Development 1983; Transportation Research Board 1988).

A Swedish study found large variation in fuel performance between different year models of cars, attributable to an additional manual gear, reductions in vehicle weight and in power to weight ratio. A 57 per cent reduction in fuel consumption would be possible if vehicle size and air and rolling resistance were also reduced, and if engine speed and efficiency were optimised, including engine shut off at zero and negative power requirements (Hammarström 1989a).

**New vehicle types**

The North American interstate truck traffic comprises mostly 5, 6, 7 or 8 axle tractor-trailer combinations, but only limited VOC data were collected for these trucks in some of the studies. Typically, values for larger trucks are extrapolated from data on smaller trucks. In the TRDF model database, for example, a 4 axle truck is the largest included. Thus, VOC of current truck operations cannot be reliably modelled. The typical trucks represented in all the VOC models are now outdated for North America where the long haul workhorse is a five-axle unit grossing up to some fifty tonnes and equipped with a 300 to 400 horsepower engine. It is gradually giving way to larger units which have lower operating costs per ton-km of shipping (Organization for Economic Co-operation and Development 1983). Two- and three-axle trucks are used mainly in urban distribution service. Inter-modal configurations such as the RoadRailer will possibly emerge in the near future (Transportation Research Board 1988).

**New engine types**

Diesel engines have long been the norm for long distance heavy hauling because they last longer, are more fuel efficient and are cheaper to maintain compared to gasoline engines. The 1960s have seen diesel engines being used more and more in medium and light weight trucking operations (Trimac Consulting Services 1990). Recent regulations of vehicle exhaust emissions have led to modified diesel fuels and changes in diesel engine design, often resulting in higher operating costs. Truck tractor engines are programmable for a specified horsepower, torque and speed for a given haul, leading to savings in fuel consumption and engine maintenance. Some engine manufacturers have introduced computer tracking of engine maintenance activities in order to further improve engine performance and operating costs. New types of engines, heat exchangers, temperature controlled fans and recycling of exhaust gases are some of the developments that can produce 10 to 30 per cent fuel savings (Organization for Economic Co-operation and Development 1983). Even mechanistic models of fuel consumption based on engine maps will eventually need a major revision to account for these changes.

**Vehicle maintenance trends**

Leading vehicle manufacturers have a goal of making “zero maintenance” vehicles. In the meantime, two developments have increased the maintenance costs of vehicles. The first is design for manufacture, which allows vehicles to be sold at lower prices but it may make later servicing more expensive. Greater use of subcontracted components may make these parts easier to replace than dismantle and diagnose, again increasing the long run costs. The designs are more complex than in the past, demanding greater skills from the service staff to diagnose and repair the vehicles. It also makes it rather difficult for consumers to fix cars themselves. The second development is the need for complex diagnostic equipment for vehicles, both on-board and in the shop. Designed to make servicing easier, the equipment makes things more difficult, because of the complexity of designs and interfaces, and the need to have specifically trained technicians to use this equipment and to interpret the readings.
Other developments

The 'unibody' design of modern automobiles integrates the chassis, the vehicle body, and even some of the mechanical components into one structure that is stronger per unit of mass than the traditional designs. Although higher ratios of strength to vehicle mass are achieved, body work and general repairs are more expensive. This is due to the fact that all components of a unibody vehicle must fit precisely in order to provide the required strength and to prevent damage to the mechanical components.

All vehicles are being equipped with radial tyres which augment the fuel efficiency and also last longer compared to bias ply tyres. Electrical systems of both cars and trucks increasingly rely on solid state technology and computerisation. This fact must have some effect on vehicle depreciation due to obsolescence and on maintenance costs. An extensive use of lighter materials in the body and mechanical components of both the truck and trailers have led to an increase in payload capacity per axle. In a quest for lighter equipment, North American truck operators consider trade-offs between vehicle durability and truck life (Bein 1990).

Fleet operation

Both private automobile and commercial fleet operating decisions respond to changes in vehicle technology and road conditions. But often overlooked is the fact that government regulation, new developments in information processing, and changes and opportunities in the marketplace are also powerful agents. In response to the changes in the economic, regulatory, and technological environment, vehicle operators endeavour to minimise the unit cost of providing the transportation service.

Regulation of the trucking industry

Recent government regulation in the US and Canada aims at releasing beneficial free market forces. Regulations regarding higher GVW, truck bans on urban roads, more uniform access for large equipment, the use of super single tyres, triple trailer combinations, and large doubles on the Interstate system are bound to significantly affect truck productivity. Other regulation, such as truck driver hours of service and limitation of vehicle emissions, will also have very significant effects on future truck operating costs and some effects on VOC of lighter vehicles. Trucking deregulation has created a trend for trucking companies to decentralise and to reduce in size (Transportation Research Board 1988). A fleet operator can lease smaller operators, allowing better adaptation to changes in the demand for transportation services, elimination of some overhead and maintenance functions, and improvement of cost productivity.

Information processing technology

Computer applications in the commercial fleet management have created a potential for productivity improvements which were not possible for the operators surveyed in the previous VOC cost studies. Computerised dispatching and routing systems can improve utilisation of vehicles by optimising the company's pickup and delivery operations. Maintenance, parts inventory, fuel and tyre control software, when used intelligently, reduce fleet operating costs and increase service reliability. Less than truckload freight can be consolidated and empty truck runs eliminated with a computerised matching service for the interchange of information between shippers and carriers. Electronic interchange of data between shippers, truckers and consignees eliminates paperwork, speeds up deliveries and synchronises the flow of goods.

Changes in the marketplace

The high-tech systems are enabling truckers to transport just-in-time (JIT). JIT is a cost-reducing method of materials and goods management in manufacture and distribution. JIT will increase in importance (Transportation Research Board 1988). JIT is also likely to reduce payloads at the expense of increased frequency of delivery. VOC savings become less important than fast and reliable delivery in the JIT service. Any revival of exports will increase long haul trucking activity, and will improve truck utilisation on return trips. In Canada, trailer-on-flat-railway-car service competes with direct trucking on longer routes (Trimac Consulting 1990).

Deregulation has shifted the risk of low productivity during periods of low demand for trucking services, from the large operators to owner operators. They are not protected from low demand and are also expected to provide service at lower unit operating costs than the large carrier. Bankruptcies are common, and it is not known when an equilibrium will be reached, or what impact it would have on VOC.

Automobiles

Advances in electronic information processing will also impact the flow, speeds and VOC of lighter vehicles, particularly in urban driving (Transportation Research Board 1988). Like truck owners, car owners can also adapt to changing
economic and road conditions. Motorists who spend most of their driving time on urban roads tend to purchase smaller, more fuel-efficient vehicles, particularly at times of high fuel prices. If the level of maintenance of the paved network decreased, resulting in increased roughness, more robust vehicles such as large cars, pickup trucks and four-wheel drives would most likely proliferate.

In North America, the cost of automotive fuel is a rather small portion of the disposable income for most households. If the fuel prices increase sharply, a car may still be preferred for personal transportation for its practical advantages, but annual distance driven will likely decrease. Travel demand management (TMD) and restraint of vehicle emissions will impose new patterns of light vehicle utilisation in urban areas. Urban congestion may lead to introducing innovative vehicles, such as the Lean Machine, to alleviate the traffic problems without eliminating the mobility afforded by a personal car (Transportation Research Board 1988).

Certainly, the current models are not suited to predict operating costs of these innovative designs, and they may not be suitable, either, to model new patterns of utilisation which the consumers are likely to develop under new TDM conditions.

**ESTIMATION METHODOLOGY**

Following this section, the major VOC models representing state-of-the-art are critiqued with respect to methodology and transferability. More extensive critique will appear in a document being prepared by MoTH.

Combined, the major models reviewed illustrate the data, the measurement methods, the approaches to prediction, and the aggregation that bear on estimation of the component consumptions of vehicle operating resources. The exceptions are rolling resistance to vehicle motion and capital costs of vehicle depreciation and interest.

**Rolling resistance**

Road surface mega- and macrotexture, and microtexture, to a smaller degree, determine vehicle rolling resistance (Descornet 1987; Sandberg 1990). Well controlled tests proved a significant effect of surface texture on rolling resistance (DeRaad 1978). Between a flush seal, hot mixes and a chip seal, the macrotexture varies by almost eight times, while microtexture by two times (Hayes and Ivey 1975). Rolling resistance is 25 per cent higher on deeply textured asphalt than on medium textured asphalt, and 50 per cent higher than on smooth concrete (Biggs 1988). The mechanistic VETO model predicts that the effect of macrotexture increase from 1 mm to 2 mm on total VOC is about two times higher than the effect due to roughness increase from bumpmeter reading of 1.46 m/km to 1.73 m/km (Hammarström and Karlsson 1987). The importance of the pavement texture variables in a VOC model is obvious.

The effect of pavement deflection bowl which forms under a heavy wheel may also be substantial on gravel roads, surface treatments and thin pavements. Drivers of laden trucks gear down in order to 'climb' the forward gradient of the bowl (Bein 1990). Notably, two of the four rolling resistance test sections in Brazil were surface treatments, and the other two were gravel sections. Consequently, the relationships derived for heavy vehicles are not likely to be appropriate to thicker pavements. Conversely, VOC relationships derived for heavy vehicles on thicker pavements (for example, TRDFVOC data) are likely not appropriate to appraise low-volume roads.

Vehicle mass, operating speed, suspension characteristics, and tyres are the main vehicle dependent variables in the rolling resistance equation, yet they are among the most uncertain highway planning data. The choice of tyre design, material, and inflation pressure affect the rolling resistance. Many vehicles are operated at tyre inflation pressures different from the recommended levels. At 67 per cent of the optimal pressure, the tyre rolling resistance increases by 33 per cent, while it decreases by 13 to 17 per cent at 133 per cent of the recommended level (Collier and Warchol 1980). Reduced tread depth in new tyres and recapping with reduced tread depth reduce fuel consumption through smaller rolling resistance (Clark 1977). But this cost reduction must be traded off with more frequent change of tyres or recapping which increase tyre costs.

**Vehicle capital costs**

Depreciation and interest costing uses the same depreciable value of a vehicle. However, there is hardly an agreement on how to predict the vehicle capital cost components as a function of age, usage and vehicle speeds. Although a relationship exists between road conditions, vehicle speed and service life, it has not been rigorously quantified.

Bennett (1989b) has studied the allocation of depreciation between vehicle age and mileage and found that age is the dominant factor but the relationships are not stable over time. Therefore
simple models, such as that by Daniels (1974), may be adequate. However, the simplistic models do not account for the relationship between maintenance, depreciation and interest, which has been identified as a crucial factor in vehicle purchase and operating policies. Only the South African VOC model can do it, based on the optimal life method (du Plessis and Schutte 1991).

Bennett and Dunn (1990) have attempted to discern the age and distance-related components of depreciation statistically and this approach is retained in the newest NZVOC version (Bone 1991) in conjunction with a capital recovery technique, which originated in South Africa (Schutte 1979).

TRDF RELATIONSHIPS AND MICROBENCOST

Billions of dollars worth of highway investments in North America are still being evaluated using the TRDF data on VOC. Model updates in the MicroBENCOST software (Texas Transportation Institute 1990), being developed under the US National Co-operative Highway Research Program, did not make a significant improvement relative to the TRDF model. The reader is referred to Bein and Biggs (1993) which reviews the TRDF VOC data and MicroBENCOST VOC submodel more extensively.

Datedness

The VOC relationships developed by TRDF are dated regarding unit costs of consumption, vehicle technology, and price relations. Vehicle technology has kept changing since 1980 for all vehicles considered in the development of the TRDF models. The TRDF formulas for fuel consumption lack a solid database for trucks larger than 2-S2. The TRDF relationships do not specify any provisions for updating for even such rudimentary factors as fuel efficiency. All trucks tested by the TRDF for fuel consumption were equipped with bias ply tyres and the aggregate industry data were also based on this type of tyres.

Judgmental relationships

Only fuel consumption was measured in controlled experiments, but the scope of road conditions was limited and judgment was used to allocate fuel costs to some road conditions. Although the TRDF researchers emphasised the need for surveys of VOC as a function of road conditions (Zaniekswski and Butler 1985), Winfrey’s judgmental factors, which were based on old vehicle technology and utilisation, were used to allocate non-fuel components of VOC. Preliminary results for road roughness from the Brazil study were used. These data have been re-estimated a number of times by the World Bank since 1981 and it is not clear whether these changes have been considered by the TRDF. Thus the limitations of both the Brazilian and Winfrey’s data would apply to the TRDF relationships.

Fuel consumption estimation

Contrary to the conclusions of TRDF researchers a significant effect of pavement surface condition on rolling resistance, and therefore on fuel consumption, was found by re-analysis of the raw data. The data contained inconsistencies, which Zaniekswski et al. (1982) managed to smooth out only to a limited extent. The fuel consumption was tested with only one specimen per vehicle type. Any unusual fuel consumption characteristics of the test vehicle would introduce errors into the fuel cost equations of that type of vehicle. The measurement of diesel engine fuel flow and measurement procedures of fuel flow during acceleration and deceleration tests were improper.

Both the proxy method used to evaluate the effect of speed changes, and the predictions of fuel consumption due to speed changes, give poor estimates. The indirect method used to evaluate the effect of curves, by comparing with power requirements on grades, is also questionable without an empirical basis.

Flaws in other VOC components

Given the above contradictions, how well were the other factors controlled in the tests? How accurate were the judgments used to derive the other VOC components as a function of road variables under different vehicle operating conditions? In a comparison with truck industry cost data (Bein et al. 1989), TRDF’s VOC relationships in the Canadian HUBAM model could not handle truck combinations with more than five axles. Uniform speed fuel and tyre consumption were greatly over predicted, and uniform speed maintenance was under predicted.

HDM-III VOC SUBMODEL

The HDM-III model is only relevant to studying rural road infrastructure design and planning issues. Although formulated for developing countries, the VOC submodel is practical and can be used in the developed countries to appraise those roads which do not experience impeded traffic flows.
Adaptation

The HDM-III relationships are complex. Any calibration or adaptation should be carried out, with a full understanding of the underlying Brazil data, physical and statistical principles, and typical highway vehicles, road conditions and unit costs in the region to which the model is adapted. Hoban (1986) saw the usefulness of HDM-III models of vehicle speeds, fuel consumption and other VOC for road evaluation and research in Australia. A Canadian study (Bein et al. 1989) recommended calibration of HDM-III VOC relationships to rural road and free-flow traffic conditions, and preliminary calibrations have been accomplished (Bein 1990; Bein 1989a) and useful results in transportation management have been obtained (Bein 1989b; Heiman et. al. 1990). Selected components of the submodel have been adapted and incorporated into the New Zealand Vehicle Operating Cost Model (NZVOC) (Bone 1991; Bennett 1989a), and into South African VOC methodology (du Pleissis and Schutte 1991).

The model will become more useful once the effects of congested and urban traffic conditions on operating speeds and costs are incorporated. To be fully useful for urban roads analysis, the model would have to take account of the additional consumption of road user inputs due to impeded traffic flow. The VOC-roughness slope needs to be validated. Since levels of roughness in the developed countries are low compared to the Brazilian database, the VOC may not be as sensitive to the effects of small changes in unevenness.

Additional road variables

The HDM-III relationships relating to rolling resistance need revision. Coast-down experiments would be required using vehicles of contemporary suspension and tyre designs on a range of typical thin and thick road surfaces in order to refine the Brazilian rolling resistance relationships. The effect of road texture on VOC may be more important than roughness effects, and will require further study since it was not addressed by the HDM research. The Swedish VETO calculated significantly lower effects of roughness-related rolling resistance on fuel consumption of cars than did the HDM-III relationship (Hammarström 1989b).

VOC components

In New Zealand, tentative modifications of the engine speed parameter of the HDM-III fuel consumption model were made until ARFCOM is implemented (Bone 1991). In South Africa, fuel consumption with HDM-III was found inaccurate, particularly for light vehicles. In British Columbia, predictions with ARFCOM were used to replace HDM-III fuel consumption estimates for all types of vehicles and road conditions.

The HDM-III has mechanistic tyre consumption relationships for trucks and buses, but not for light vehicles due to inadequate data collection. The prediction of tyre consumption is based on a synthesis of mechanistic models, which has been also utilised by the TRDF for both light and heavy vehicle types. This model was not adopted in South Africa, where an empirical model was found to better suit local data.

Maintenance and depreciation costs need closer examination. Vehicle speed and truck mass do not appear in the HDM-III equations, although industry experience points out that these variables are major on rougher roads (Trimac Consulting 1990). Maintenance cost formulas need re-evaluation for the prevailing economic conditions in the new region since the economy of Brazil was characterised by a low cost of labour. South Africa has adopted the HDM-III relationships as acceptable for light vehicles and buses, while for trucks HDM-III was found inadequate (du Plessis and Schutte 1991).

The various techniques available in HDM-III for depreciation and interest costs must be used with caution as each one produces different results. The approach relies on more assumptions than that for fuel consumption, tyre wear and vehicle speeds. The present relationships for vehicle capital costs reflect shorter-term impacts on utilisation. The HDM-III 'adjusted utilisation' method should be modified for commercial vehicles to account for the fact that travel time savings do not necessarily translate into additional trips. The longer-term effects of road conditions on fleet utilisation need to be included.

Although the market value of a vehicle declines with the passage of time and with the amount and type of usage, very limited data were collected in the Brazil study to estimate the relative contributions. No explicit relationships between depreciation and interest costs and road characteristics are possible in HDM-III. Any functional dependencies on road conditions materialise through the effect of road characteristics on vehicle speed in the 'adjusted utilisation' method. Analysis based on constant service life and utilisation does not differentiate between time and use related depreciation. It neglects any residual vehicle values, does not consider the fleet age spectrum and ignores non-linearity of
depreciation. The optimal life method (Chesher and Harrison 1987) has not been included into the HDM model.

Cost differentials due to highway investment cannot be determined from de Weile’s ‘varying life method’, because changes in speed do not affect use levels in the short to medium term. If a road is improved, lower vehicle maintenance costs should alter the market value, service life and depreciation of the vehicle. The ‘value-age method’ is typically insensitive to these effects. The South African researchers rejected the HDM-III approach as ambiguous and invalidated with respect to the effect of vehicle speed on depreciation (du Plessis and Schutte 1991). The ‘varying life method’ was found unsuitable for low vehicle utilisation levels in New Zealand. The ‘adjusted utilisation method’ is not fitting either (Bennett 1989b). Utilisation may vary with road conditions as the operators attempt to adapt operating hours to maintain low total VOC.

AUSTRALIAN VOC MODELS

Both the rural and urban VOC methodologies rely heavily on functional relationships developed in Australia in the early 1970s. It is doubtful whether the data warranted the complex set of functional relationships in NIMPAC, and it is not clear how the urban formulae were derived (Abelson 1986).

VOC functions in NIMPAC

The cost functions were developed between 1968 and 1973 from an assortment of domestic and overseas studies, and have not been varied significantly since then. NAASRA considered that the VOC of large trucks are overestimated in NIMPAC and attributed this to the improved performance of trucks over the last decade. The model does not include large truck combinations which are now more common in Australia. It appears that NIMPAC development placed unrealistic demands on the available evidence. Consequently, many of the cost functions in the model are questionable and difficult to substantiate. Lawlor (1982) criticised the cost relationship of

- fuel consumption vs speed changes, curvature, and type and condition of surface,
- tyre consumption vs vehicle speeds, road surfaces and gradients,
- vehicle maintenance vs surface types and condition.

Despite the valid criticisms, Abelson (1986) judged the VOC estimates in NIMPAC to be realistic for Australian rural road conditions, and consistent with results in international studies. This is likely due to a careful up-dating of vehicle types and unit costs.

Aggregate urban VOC formulas

The constants in the standard aggregate formulas used to estimate VOC on urban roads are based on estimates for vehicles and prices in 1973-1974. The users have to update these estimates with changes in the CPI rather than with specific vehicle and cost factors. The values of the constants are derived from dated data which were never robust, and which are difficult to up-date. The users have to update the constants with changes in the CPI rather than with specific vehicle and cost factors. The data relied on older studies in which aggregate estimates of tyre and maintenance and repair costs were factored up using ratios to fuel cost. The implicit assumption that tyre wear and maintenance costs are related to speeds in the same way as fuel consumption has little experimental justification. Also, the estimates were reported for speeds up to 52 km/h and extrapolations to 100 km/h are too daring. Given these limitations, Abelson (1986) found the following flaws in the standard aggregate urban VOC formulas:

- discrepancies in VOC estimates at high speeds on freeways vs roads without access control,
- underestimation of VOC by the urban models, compared to his own and NAASRA (1985) data,
- overestimation of VOC savings of cars and trucks at higher speeds, compared to his own and NIMPAC estimates.

ARFCOM MODEL

The ARFCOM model of fuel consumption is an internationally verified world leader suitable for both rural and urban traffic and transport management applications in different planning cases. Its user-selectable level of aggregation makes it appropriate to use with any vehicle speed prediction method, ranging from a simulation of urban driving to an aggregate speed prediction model. A simplified ARFCOM has been tested on the Canadian car fuel consumption 1986 survey data. The under-estimation of fuel consumption by the model in that study was assumed to be due to the effect of cold starts, but this was not demonstrated. ARFCOM in that study has
also determined the following effects on fuel consumption of cars (Biggs 1989):

- changes in stopping and slowdowns, average traffic speeds and traffic volumes on urban streets,
- changes in average speeds on rural highways and freeways, and
- improvements in engine size and efficiency, aerodynamic drag, rolling resistance, mass, tyre maintenance, fuel cut-off when stopped and ability to re-use energy dissipated in the brakes.

A comparison between ARFCOM estimates and fuel consumption observed in heavy Canadian trucks used in inter-city service (Biggs 1989) demonstrated that ARFCOM is a truly mechanistic model which can be easily calibrated and adapted to the following new conditions:

- different country and climate,
- different vehicle technology and weight regulations, and
- extrapolation to larger trucks than Australian vehicles used in the development of ARFCOM.

VETO MODEL OF TRANSPORTATION COSTS

The Swedish VETO is based on physical modelling of causative factors. Therefore, it is transferable, provided a calibration of its coefficients is carried out to suit the road conditions, vehicle operation, vehicle characteristics and driver behaviour modelled by VETO. The model has been used in Sweden to calculate exhaust emissions. This makes the model extremely useful for highway planning needs. Although it is detailed and requires extensive inputs, VETO can be useful for analyses requiring more aggregate VOC data. Such data could be developed by running the model on a set of representative vehicle, road geometry and road condition characteristics, as has been already done in Sweden for numerous planning studies.

The model still needs validation of some of its relationships. Only the fuel consumption and the forces in a light vehicle as a function of longitudinal roughness have been validated. The authors of VETO are not satisfied with the state of knowledge on the effects of road roughness on fuel consumption. Different studies indicate different results. Based on Ross (1981), VETO gives smaller effects than other studies. Lack of data is not the problem as much as how to judge what to use. VETO can account for air drag due to air turbulence and vehicle oscillations due to roughness, but there are no definitive data to calibrate against.

The most uncertain is perhaps the calculation of vehicle maintenance costs which has been tentatively calibrated from the Brazil study. An alternative model based on fatigue mechanics cannot as yet produce a result in monetary units. However, the approach is fresh and promising. Tyre consumption prediction in VETO is based on the mechanistic models developed in the United States, i.e. the same source as in the mechanistic HDM-III equation for trucks and buses.

COBA

The present version, COBA9, is suitable for appraisals of rural and inter-urban road schemes only, but it is being extended to urban trunk roads. This on-going work is expected to produce COBA13 (Allsop et al. 1986). Many inbuilt relationships are unique to the United Kingdom, for example the speed-flow relationships. COBA is practical, simple, has uniform procedures, and VOC input data are standardised. COBA represents a well balanced, common sense approach to both VOC models and data.

For its level of detail and aggregation of inputs, COBA seems more suitable for comparisons of alternative highway investment strategies and road schemes than for evaluation of detailed design solutions. Road geometry enters most of the VOC relationships indirectly through the effect on the flow of traffic and operating speed of vehicles. There are only four sample vehicles in the model and larger trucks are not adequately represented. The COBA approach used with netting the cost of fuel should be examined for tyres, spare parts and vehicle purchase prices, in order to determine what part, if any, of the tax saved through highway investments would be recovered by the governments through increased indirect general taxation.

Leitch (1977) reports on a sensitivity analysis of a sample of 25 non-urban road improvement projects. An increase in vehicle capital savings of 30 per cent did not have any significant impact. The predicted free flow speed had the most important effect on VOC, followed by junction capacity and traffic assignment, as most of the projects were time saving bypasses. COBA's ranking of schemes proved highly sensitive to the proportion of heavy trucks in the traffic mix, since it affects both VOC and traffic flows.
**SOUTH AFRICAN VOC MODELS**

South African work in VOC has been directed at determining the applicability of the results of international VOC studies to local data. Reasonable conformity with the Brazil data was obtained for many of the relations. In the process, new data of international relevance were produced with respect to rolling resistance effects on fuel consumption, and aggregate type on tyre wear.

In modelling the effects of road conditions on maintenance costs, the vehicle parts are classified into a number of categories, each affected by a different road and vehicle operating condition (Pienaar 1985). The South African researchers derived depreciation and interest cost equations from an economic model of the optimal life (du Plessis and Schutte 1991).

**CONCLUSIONS**

Only the mechanistic models (VETO, ARFCOM, and partly HDM-III) are transferable between the conditions they were derived from and the new conditions of a particular application. Modelling of either cold-start fuel consumption, rolling resistance, maintenance, or vehicle capital cost, or a number of these relationships need improvement in all of the models. The TRDF model and its application in MicroBENCOST are not suitable for use in North American road management. HDM-III needs more work for applications to impeded traffic flows, and its roughness —VOC slope should be investigated for sensitivity to small changes in pavement unevenness which are more typical in developed countries compared to the Brazilian conditions. This slope is being adopted by many other models. NIMPAC is currently under revision, and NZVOC and COBA are being updated. South African approaches to several vehicle operating cost components as a function of road conditions represent a significant advancement in state-of-the-art models. VETO would be a champion if it had a PC version. ARFCOM also stands out among its competitors, but it is limited to fuel consumption estimation.

Most affected by the limitations of the VOC models are the appraisals of urban transportation projects, which will likely dominate infrastructure budgets in the foreseeable future.

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