The New Zealand Vehicle Operating Costs Model

CHRISTOPHER R. BENNETT

The development of a computer model to predict vehicle operating costs for use in highway economic appraisals is described. Like many smaller, less wealthy countries, New Zealand did not have the capital or resources available to conduct its own research into vehicle operating costs. After an extensive literature review, it was decided to adopt the World Bank's HDM-III Brazil operating cost relationships and an Australian model for passenger car and light commercial vehicle fuel consumption. Depreciation costs were calculated using the results of a New Zealand study that successfully differentiated between the use and age-related components. A computer model was developed that used these relationships to predict vehicle operating costs. It was used to prepare tables of costs for use in manual appraisals and to analyze individual segments of roads. It employs a three-zone, speed-volume model to consider traffic interactions on individual segments of road. For all calculations, the model uses standardized distributions of vehicle speeds. These associate a range of speeds with a mean value to calculate a composite cost that reflects the entire range of speeds of all vehicles traveling in the traffic stream.

Low-volume roads pose a difficult problem for highway authorities throughout the world. Whereas improvements to roads that carry high volumes usually accrue substantial benefits, the benefits for low-volume roads are relatively low and the economic justification of improvements is often marginal. It is therefore essential that all investments in low-volume roads be screened so that only the economically feasible projects are allowed to proceed. Ideally, screening should be achieved by a rigorous economic appraisal that compares the project costs with the benefits in the form of travel time savings and reduced vehicle operating costs.

HIGHWAY ECONOMIC APPRAISALS IN NEW ZEALAND

New Zealand is a small country with a population of 3.3 million and a land area of 268,105 km^2. With a Gross Domestic Product of approximately $7,000 (U.S.) per capita, New Zealand is one of the least wealthy of the Organization of Economic Co-operation and Development countries. The major export industries are related to primary produce. The rural sector is serviced by some 80,000 km of roads and there are approximately 18,000 km of urban roads.

Most of the population is centered in the major coastal cities; the majority of the rural roads therefore carry low volumes. In a recent study of the roading network, it was estimated that the average traffic on 26,000 km of sealed roads was 320 vehicles per day (vpd) and 76 vpd on 42,000 km of unsealed roads (*1*).

With such a dispersed network supported by a small population and limited resources, the roading authorities recognized the importance of economic appraisals quite early. Economic appraisals were first discussed in the 1940s in the context of the effects of different alignments on operating costs and maintenance policies (*2*). In the late 1960s they became widely accepted and in 1971 the first standard techniques for highway economic appraisals were introduced (*3*).

The use of economic appraisals has increased rapidly and it is now required that all projects receiving funds from the Treasury be shown to be economically viable. This has led to the recent publication of a Technical Recommendation for the Economic Appraisal of Roading Improvement Projects called TR9 (*4*). This publication provides a relatively simple manual method for conducting economic appraisals. It also provides curves and tables of vehicle operating costs that can be used in the appraisals.

The Prediction of Vehicle Operating Costs for Economic Appraisals

The most important element of an economic appraisal is the accurate prediction of the vehicle operating costs. In preparing TR9 it was decided that it would be necessary to employ operating cost relationships that were developed overseas because insufficient time or funds were available to develop such relationships within New Zealand. This situation is common in many of the less wealthy countries that have insufficient capital or resources available to conduct their own research. Fortunately, the literature abounds with the results of research into predicting vehicle operating costs. The main difficulty therefore lies in selecting the most appropriate relationships for the country in question.

It is possible to broadly categorize the research into that which was conducted before the 1970s and that which was conducted since then. Research into motor vehicle fuel consumption began in the 1920s and the major emphasis was on the advantages of gravel and paved surfaces over dirt surfaces (*5*). It was not until the 1950s, however, that research into all aspects of vehicle operating costs became common, and in the late 1960s and early 1970s a number of works were published that compiled the operating costs that were related to road design standards. A summary of the early works and a description of the data bases on which they were based can be found elsewhere (*6*).

A number of deficiencies are associated with this early work. Several authors used personal judgment to supplement data bases that were of questionable accuracy. Claffey used direct experiments augmented by surveys, which makes his study the

W. D. Scott Deloitte Ltd., P.O. Box 2459, Auckland, New Zealand.

most reliable of the early works; however, the vehicles that were used bear little resemblance to the modern vehicle fleet (*7*). In spite of these deficiencies, a number of authorities still use these early, outdated operating cost estimates for economic appraisals.

In 1969 the World Bank initiated a program to investigate the interrelationship between construction, maintenance, and vehicle operating costs on low-volume roads. Because of the lack of reliable information, a major user cost study was undertaken in Kenya from 1971 to 1975 that investigated paved and unpaved road deterioration and factors that affect vehicle operating costs (*8, 9*). User cost studies were later conducted in the Caribbean, India, and Brazil (*10-13*).

The results of these studies have been incorporated by the World Bank into their HDM-III model (*14*). The World Bank staff has also reanalyzed much of the Brazil study to develop modified Brazil relationships specifically for use in the model. The HDM-III model is a comprehensive macroscopic model that represents the state of the art in economic appraisals of low-volume roads. It can be used to optimize highway investments on a national level. However, because of its complexity, it is unsuitable for use in microscopic evaluations of the type that are undertaken in New Zealand.

It was therefore decided to undertake the development of a model for use in New Zealand that was based on HDM-III but tailored more to New Zealand's small-scale requirements. The model would also be used to prepare tables and curves of vehicle operating costs that could be used in manual appraisals. This led to the development of the New Zealand Vehicle Operating Costs (NZVOC) model.

THE NEW ZEALAND VEHICLE OPERATING COSTS MODEL

The NZVOC model was developed at the University of Auckland (*15*). After the operating cost relationships in HDM-III and others available in the literature were evaluated, it was recommended that the HDM-III Brazil relationships be used in New Zealand to predict all operating costs except passenger car and light commercial vehicle fuel consumption. It was believed that Caribbean relationships would be more appropriate for these categories. In addition, depreciation relationships were developed from a study of New Zealand vehicles and a modified Transportation Road Research Laboratory (TRRL) methodology was used to estimate the costs (*15*).

The Brazil and Caribbean relationships were selected after considering the data bases from which they were developed, the operating conditions in the original studies, and the relevance of the study vehicles to New Zealand. This type of an evaluation should be undertaken whenever overseas relationships are being considered for use because only then can it be ensured that the resulting operating costs are relevant and can be used with a measure of confidence.

For the TR9 project, the NZVOC model was rewritten and enhanced to form the NZVOC2 model. In the NZVOC2 model, the Caribbean relationships were replaced by relationships that were developed in Australia because these were found to be more applicable for use in New Zealand. The same relationships that were in the original NZVOC model were used for the other cost components.

The features of the NZVOC2 model and examples of its predictions are described in the following sections. A complete discussion of the model's structure, operating cost relationships, and input data can be found elsewhere (*16, 17*).

Representative Vehicles

The NZVOC2 model considers six classes of representative vehicles: passenger cars, light commercial vehicles, medium commercial vehicles, two groups of heavy commercial vehicles (HCV-I and HCV-II), and buses. This system was selected by considering the nature of the New Zealand vehicle fleet and the available operating cost data.

The use of six vehicle classes provides analysts with more flexibility in calculating the operating costs for different traffic conditions. It is important that operating costs reflect the costs of the entire vehicle class; this is achieved by basing them on the costs for a number of different vehicles within the class. The costs for the individual vehicles are then aggregated into a composite cost that can be considered to be representative of all vehicles in the class. A total of 15 representative vehicles are used in the modeling; they are summarized in Table 1 (*17*).

Unit Costs

One of the most useful features of the more recent operating cost relationships is the way in which they estimate vehicle operating costs in terms of the consumption of resources. This consumption is multiplied by the costs of the different components to obtain the financial or economic cost. When preparing standard estimates of vehicle operating costs, it is therefore possible to quickly revise the costs to reflect changes in the costs of the individual components. This is a useful feature in countries with high inflation rates in which cost estimates should be frequently updated. It also means that it is not necessary to resort to the use of inflation indices for the cost updating. These indices often reflect changes in costs outside of the transport sector. The values of the economic costs of the various components that were used in the TR9 project are summarized in Table 2 (*18*).

Vehicle Operating Costs

As was discussed earlier, the NZVOC2 model draws mainly on the World Bank HDM-III model for its vehicle operating cost relationships. The relationships used to predict vehicle speeds and the various operating cost components are summarized in Table 3.

It is impossible here to reproduce the actual relationships in their entirety. Readers interested in the form of the relationships should refer elsewhere for a complete discussion of their theoretical development (*19*). However, a discussion follows of the nature of the relationships and why they were selected for use in New Zealand. The Brazil models discussed are those developed by the World Bank for the HDM-III model and are not the original relationships developed in Brazil (13, 14).

Speed

Because economic appraisals generally consist of evaluating the effects that the alteration of roadway characteristics will have

TABLE 1 REPRESENTATIVE VEHICLES USED IN THE NZVOC2 MODEL

Vehicle Class	Vehicle	Type of Fuel	Percentage of Vehicles
Passenger car	Small passenger car	Petroleum	82.0
	Medium passenger car	Petroleum	18.0
Light commercial	Light van/utility	Petroleum	50.0
	Medium van/utility	Petroleum	35.0
	Light truck/heavy utility	Petroleum	10.0
	Light truck/heavy utility	Diesel	5.0
Medium commercial	4-tonne truck	Petroleum	7.0
	4-tonne truck	Diesel	26.0
	6-tonne truck	Diesel	34.0
	8-tonne truck	Diesel	33.0
Heavy commercial (HCV-I)	15-tonne, 3-axle truck	Diesel	100.0
Heavy commercial (HCV-II)	Multi-axle/artic. truck	Diesel	75.0
	Multi-axle/artic. truck towing	Diesel	25.0
Bus	Urban bus	Diesel	50.0
	Rural bus	Diesel	50.0

TABLE 2 UNIT COSTS USED IN 1986 COST CALCULATIONS[a]

Vehicle Class	New Vehicle ($/veh)	New Tire ($/tire)	Labor ($/hr)	Petroleum ($/liter)	Diesel ($/liter)	Engine Oil ($/liter)
Passenger car	14,100	125	27	0.6697	-	3.558
Light commercial	14,100	125	27	0.6697	-	3.558
Medium commercial	32,800	225	27	0.6697	0.5848	3.558
Heavy commercial (HCV-I)	101,051	410	27	-	0.5848	3.558
Heavy commercial (HCV-II)	143,400	410	27	-	0.5848	3.558
Urban bus	140,600	410	27	-	0.5840	3.558
Rural bus	231,800	410	27	-	0.5848	3.558
Trailer	30,400	410	27	-	-	-

Notes: Dash = no cost applicable. All costs in New Zealand dollars ($1.00 New Zealand = $0.55 U.S.) as of April 1, 1986

TABLE 3 NZVOC2 MODEL VEHICLE OPERATING COST RELATIONSHIPS

Vehicle Class	Component Speed	Fuel	Tires	Oil	Parts	Labor	Depreciation
Passenger car	Brazil[a]	ARRB[b]	Brazil	HDM-III[c]	Brazil	New Zealand	New Zealand
Light commercial	Brazil	ARRB	Brazil	HDM-III	Brazil	New Zealand	New Zealand
Medium commercial	Brazil	Brazil	Brazil	HDM-III	Brazil	New Zealand	New Zealand
Heavy commercial (HCV-I)	Brazil	Brazil	Brazil	HDM-III	Brazil	New Zealand	New Zealand
Heavy commercial (HCV-II)	Brazil	Brazil	Brazil	HDM-III	Brazil	New Zealand	New Zealand
Bus	Brazil	Brazil	Brazil	HDM-III	Brazil	New Zealand	New Zealand

[a]Relationships developed by the World Bank from Brazil study data not GEIPOT relationships.
[b]Australian Road Research Board relationships.
[c]Relationships developed for use in World Bank HDM-III model.
[d]New Zealand developed or modified relationships.

on time and operating costs, it is necessary to use a method by which the impact of these changes on vehicle speeds can be quantified. This is not only useful in an economic appraisal, but it can be used to evaluate the optimum, or preferred, alignment during the planning stages.

The Kenya, Caribbean, and India studies developed linear regression models that related the effect of geometry on vehicle speeds. A typical relationship from Kenya is as follows (*8*).

$$V = 102.6 - 0.372RS - 0.076F - 0.111C - 0.0049A \quad (1)$$

where

V = mean speed of cars in km/hr,
RS = average rise in m/km over the road segment,
F = average fall in m/km over the road segment,
C = aggregate curvature in degrees/km, and
A = altitude in m above sea level.

A complete set of equations is given in a study by Bennett in which their predictions are discussed and compared (*15*).

Regression equations of this nature have two major shortcomings (*20*). An inconsistency exists in the coefficients between the equations from the various studies, which is partly a result of the high degree of correlation between road characteristics. Curves and grades are often found together and the regression procedure may not correctly isolate the independent effects of curves and grades.

The second shortcoming is that the regression equations are unable to handle extreme conditions. It is possible to obtain negative values of speed for reasonable combinations of road characteristics. Furthermore, the geometric effects have a constant effect regardless of the values of other geometric features. This means, for example, that speeds on a steep upgrade could be increased by making the surface smoother even though the gradient is the speed-limiting factor and not the surface condition (*20*).

The World Bank developed an alternative method of modeling speed-geometry effects for the HDM-III model using data from the Brazil study (*19*). The method assumes that each vehicle has a set of limiting maximum speeds for open roads, upgrades, downgrades, curves, and rough surfaces. At any given point, the speed will be the minimum of these five values.

The Brazil model provides equations that relate each of these limiting speeds to road geometry and roughness characteristics. The model is based on mechanistic principles and requires data that detail vehicle mass, load, frontal area, and aerodynamic drag. It also uses a number of vehicle and driver parameters that were quantified from the field data of the Brazil study.

The effects of grade in the Brazil speed prediction model are depicted in Figure 1. At low grades, the steady state speed is governed by the psychological, roughness, and curve constraints. As the grades become more pronounced, the effects of the other constraints lessen until the only constraint is that which results from the gradient.

The Brazil model is conceptually more attractive than the simple linear models because it is based more firmly on principles of driver and vehicle behavior. Concerns have been expressed about the techniques used to quantify the model parameters; however, it still constitutes the best speed prediction model currently available (*20*).

Before the model could be applied in New Zealand, it was necessary to calibrate its predictions. This should ideally take the form of requantifying all regression-based model parameters. Because such an undertaking was beyond the scope of the TR9 project, it was assumed that the effect of geometry on vehicle speeds observed in Brazil would apply in New Zealand and that therefore the regression-based values would be applicable. Therefore, only the desired speed constraint was changed so that the Brazil model would give predictions similar to what were observed on flat, straight roads with average roughness levels in New Zealand.

Fuel Consumption

Both the Australian Road Research Board (ARRB) and the Brazil fuel consumption models are based on mechanistic principles and have the same underlying structure (*21*). The ARRB model was selected for passenger cars and light commercial vehicles in preference to other models because the vehicles on which it is based are more similar to what are found in New Zealand. Its predictions can also take urban traffic interactions into consideration. Accordingly, TR9 contains two

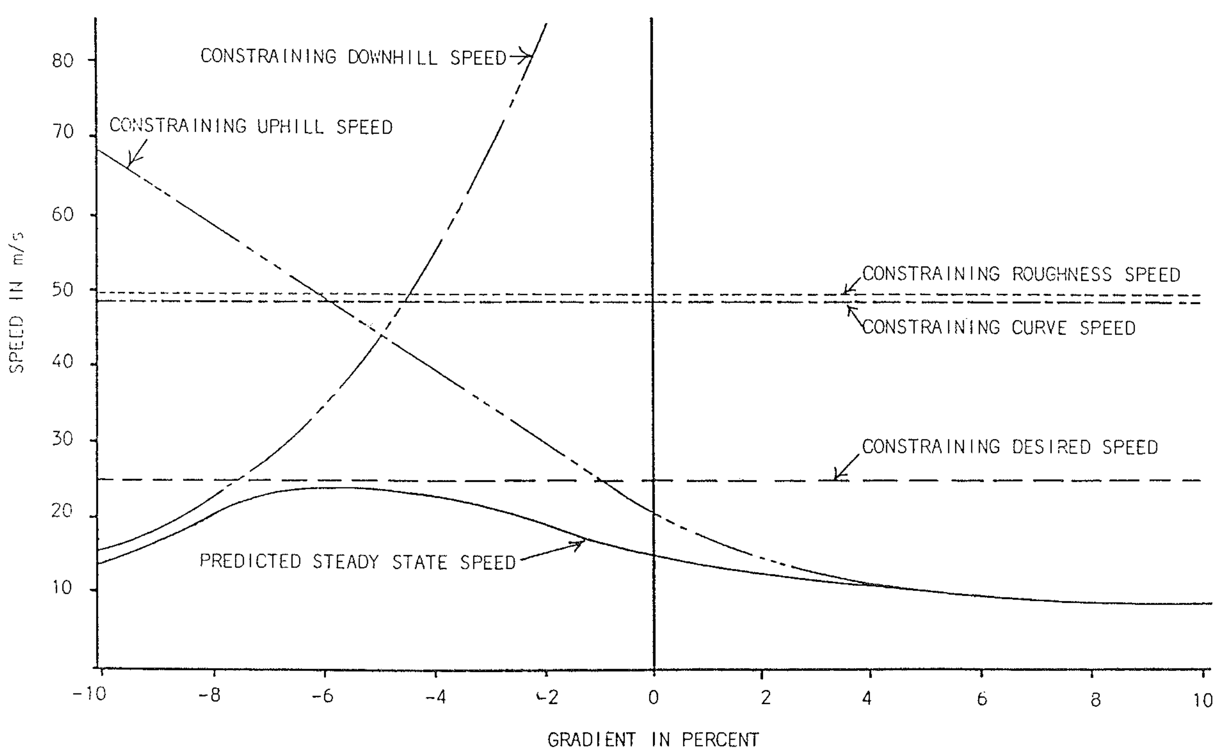

FIGURE 1 Constraining and steady-state speeds versus gradient.

sets of fuel costs for passenger cars and light commercial vehicles; one is for urban conditions and the other is for rural, free-flowing conditions.

The Brazil relationships are the only mechanistic models available for predicting the fuel consumption of a range of commercial vehicles. Unfortunately, technological changes to vehicles since the mid-1970s may have rendered these models obsolete for some applications. Because the average service life of commercial vehicles is approximately 15 years, this is not considered to be a significant problem in New Zealand (*15*). However, for countries with low vehicle service lives, use of these models may result in an overprediction of fuel consumption.

The accuracy of the fuel consumption models was evaluated on a macroscopic level in another study (*1*). When using annual traffic volume data for all of New Zealand, it was found that the predicted petrol consumption calibrated to within 5 percent of the observed national petrol consumption. The diesel consumption calibrated to within 63 percent. However, a large segment of the difference was ascribed to an inability to accurately specify the commercial vehicle traffic composition. Overall, the models were considered to give a good representation of motor vehicle fuel consumption.

Tire Consumption

The Kenya and Caribbean studies both developed tire consumption relationships that employed roughness as an independent variable. Vehicle mass was employed as an independent variable for trucks. The India study relationships related tire consumption to a wide range of road characteristics, including width, curvature, roughness, and gradient. For cars and light commercial vehicles, the Brazil tire consumption model is a simple, linear relationship with roughness as the independent variable. A more complex model that is based on mechanistic principles has been developed for trucks and buses.

It was decided to adopt the Brazil model to predict passenger car tire consumption. The India model was considered to be unsuitable because it was believed that the New Zealand road and traffic characteristics were significantly different from those encountered in the India study. The Caribbean study did not include observations at low roughnesses, which are commonly encountered in New Zealand. The Kenya model was rejected because the tire lives appeared unreasonably high in the New Zealand context. The Brazil model was selected for commercial vehicles because its mechanistic basis made it superior to those of the other studies.

There are two components to tire consumption: tread wear and carcass wear. The Brazil mechanistic model predicts tread wear as a function of the wearable volume of rubber and the forces that act on the tire. Carcass wear is considered in terms of the number of retreads that the carcass may be suitable for, which is affected by the road roughness and curvature.

In developing the model, it was found that insufficient data existed to quantify the effects of lateral forces on tire wear (*19*). This is a serious shortcoming of the model. Lateral forces are only considered through a very approximate relationship between superelevation and curvature. A second deficiency in the model may be in the assumptions employed in considering retreaded tires. The findings of the Brazil study are in conflict with those of other studies (*15, 20*).

In spite of these shortcomings, the Brazil mechanistic model offers a significant advancement over the other regression-based models. Because it considers the effects of forces on tire wear, it is the most versatile model and, therefore, the most readily transferable between countries.

Oil Consumption

The costs of oil and lubricants are calculated using the HDM-III model (*14*). This model was developed after considering the results of a number of studies on the effects of operating conditions on oil consumption. It consists of a base rate of oil consumption and a linear term that is a function of surface roughness. The constant of the linear term is surprisingly the same for all vehicle types even though the base rates vary significantly.

It was believed that the model gave predictions for passenger cars and light commercial vehicles that were excessive in the New Zealand context. This difference is probably a result of the type of light vehicles found in New Zealand and local maintenance practices. The base rates of consumption for these vehicles were reduced by 1.0L/1000 km to rectify the situation.

Parts Consumption and Labor Costs

Particular care must be taken when applying parts and labor models that were developed in different countries. Maintenance and repair costs are affected by management decisions and operating conditions. Therefore, it can be anticipated that significant variation will exist in these costs not only between countries but perhaps between different regions of the same country. Labor costs will show the greatest variation with location; so calibration exercises should therefore focus on these costs.

The Kenya, Caribbean, and Brazil parts consumption models use road roughness and distance traveled as independent variables. The India study related parts consumption to these and other variables that reflect roadway geometry.

The India relationships were excluded from consideration for use in New Zealand because the traffic stream in India is heterogeneous and is composed of a range of vehicles, from bullock carts to auto-rickshaws. These conditions make the India relationships unsuitable to countries with significantly different traffic conditions.

The Caribbean model is not based on observations of the relatively low levels of roughness that are commonly found in New Zealand. As illustrated in another study, this factor, and the nature of the model structure, result in unreasonable predictions. The Kenya passenger car and light commercial vehicle relationships are also not based on observations at low roughness levels, although the range of roughness considered encompasses the majority of roads in New Zealand.

The only parts consumption model that encompasses the complete range of roughness levels found in New Zealand is the Brazil model, and it is also based on an extremely comprehensive data base. It predicts that the impact of roughness on parts consumption will generally increase with increasing roughness, which is a logical response. It was therefore decided to adopt the Brazil parts consumption model for use in New Zealand.

Because of the concerns discussed earlier in regard to the transferability of the labor models, it was decided not to employ a labor model that was developed in one of the user cost studies. It has been suggested that the ratio of parts to labor costs lies in the range of 50:50 to 60:40 (*22*). The approach adopted was to have a constant cost based on a 55:45 split between parts and labor costs. This value was selected because parts in New Zealand comprise a slightly larger portion of the total maintenance and repair costs than labor.

Unlike the other component costs, estimates of maintenance and repair costs based on New Zealand surveys were available. It was clearly desirable to calibrate the Brazil parts consumption model so that its predictions were the same as these known values at average roughness values. Two methods were available for calibrating the model; the model parameters could be modified or a constant term, which may be negative, could be added to the predictions. As was illustrated in another study, the latter is the only appropriate method, because it does not affect the impact of the independent variables on the model predictions (*15*).

The parts model was therefore calibrated by first determining the parts component of the New Zealand costs based on the 55:45 split between parts and labor costs. A constant term was then added to the Brazil model predictions so that they gave the same values at an average roughness level.

Depreciation

The depreciation expense of a motor vehicle arises as a result of usage, age, and technological obsolescence. The use-related depreciation should be treated as a running cost. The age and technological obsolescence costs are overhead costs because they occur independently of vehicle use. For TR9, the depreciation costs are calculated using the relationships and methodology established in another study (*15*). It was found that passenger car and commercial vehicle depreciation could be predicted using relationships of the following form:

Passenger cars: $DEP = C\ (AGE)^A\ (KILOM)^B$ (2)

Commercial vehicles: $DEP = C - D\ (AGE)^A\ (KILOM)^B$ (3)

where

DEP	=	depreciation of a vehicle as a percentage of the vehicle replacement price,
AGE	=	age of vehicle in years,
$KILOM$	=	cumulative kilometrage of vehicles, and
A to D	=	constants.

These depreciation relationships were established using the following methodology:

- Data on recent resale values of motor vehicles, and their age and distance traveled, were collected from newspapers and dealers' guides.
- The original retail value of vehicles was determined and inflated into current dollars.
- The depreciation (as a percentage) is the difference between the inflated original value and the recent resale value.
- An SAS nonlinear regression package was used to relate the vehicle depreciation to its age and distance traveled (constants A to D in Equations 2 and 3) (*23*).

The use of these relationships in conjunction with the age and cumulative kilometrage data enable the value of a vehicle at any stage of its life to be calculated. These data can then be aggregated to provide a single value to express depreciation costs for the fleet. This process can be mathematically expressed as follows (*17*):

$$DEPCOF = \sum_{i=1}^{n} FREQ_i\ CDEP_i \qquad (4)$$

where

$DEPCOF$	=	depreciation coefficient,
$FREQ_i$	=	percentage of vehicle of age i in the fleet, and
$CDEP_i$	=	change in depreciation over year i.

The variable $CDEP_i$ is defined as follows:

$$CDEP_i = DEP_i - DEP_{i-1} \qquad (5)$$

The annual depreciation costs are obtained by multiplying the depreciation coefficient by the replacement price of a vehicle.

The weighting of the exponents in the depreciation relationships gives the relative percentages of the total depreciation that result from use and age. The following are percentages of the total depreciation that results from vehicle use: passenger cars—40 percent, light commercial vehicles—30 percent, other commercial vehicles—20 percent, and buses—20 percent.

Vehicle Speeds

Economic appraisal techniques generally have not adequately considered the sensitivity of vehicle operating costs, particularly fuel costs, to operating speeds. The standard practice is to estimate the mean speed of the traffic stream using models such as those discussed earlier and then calculate the vehicle operating costs that correspond to this speed.

This practice ignores the fact that the average speed of vehicles on a road is composed of a distribution of speeds. The costs that correspond to each speed in the distribution should be calculated and then combined to form a composite speed cost for a stream of vehicles with a given mean speed. This composite cost can be calculated using the following relationship (*17*):

$$COMCOST = \sum_{i=1}^{n} COST_i\ SPFR_i \qquad (6)$$

where

$COMCOST$	=	the composite speed costs for a stream of traffic with a mean speed of V,
$COST_i$	=	the cost of a vehicle traveling at speed i,
$SPFR_i$	=	the number of vehicles in the stream traveling at speed i, and
n	=	the number of different speeds in the distribution.

As was discussed in another study, when individual spot speed observations in a sample are divided by the sample mean

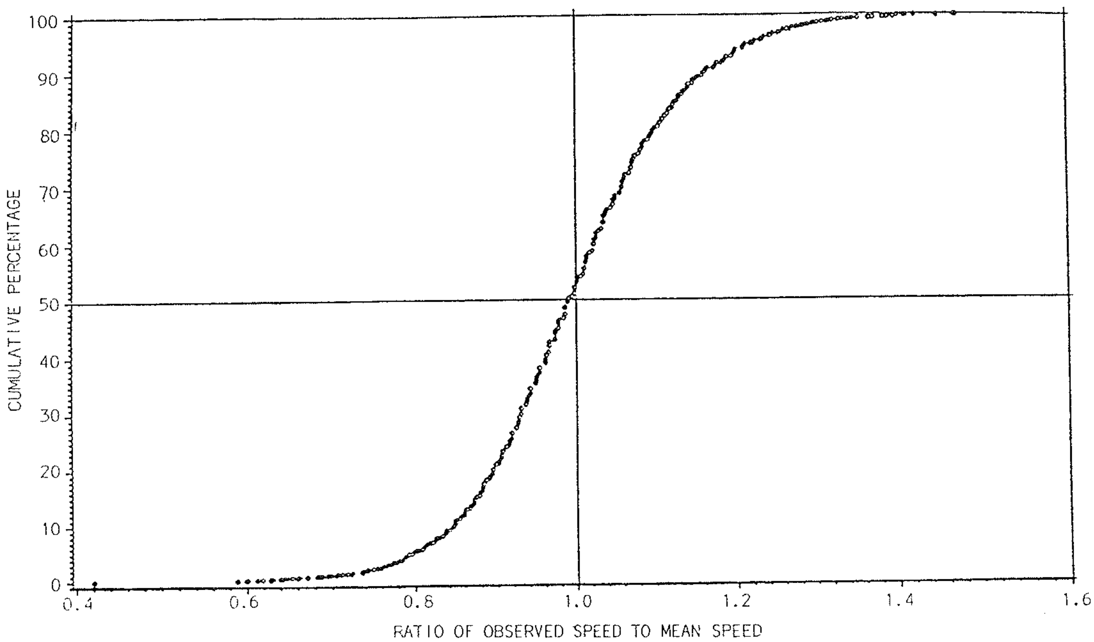

FIGURE 2 **Standardized passenger car speed distribution.**

speed, the resulting standardized distribution is identical to standardized distributions from other sites (*24*). Data from six spot speed studies that were conducted throughout New Zealand were used to establish standardized distributions for nine different vehicle classes. Figure 2 is an example of the standardized passenger car distribution (*24*).

Standardized distributions make it possible to fully describe the speed distribution solely from the mean speed. They provide details of the the range of speeds associated with the mean value and also of the number of vehicles that can be found over the range. Given a mean speed, which can either be predicted using the Brazil speed prediction model or estimated by the user, the NZVOC2 model uses the appropriate standardized speed distribution for the vehicle class to calculate the composite speed costs. This results in differences in fuel costs of up to 10 percent over those associated with the mean speed.

Speed-Volume Effects

Speed-volume effects are an important consideration in economic appraisals. Traffic delays on rural roads are usually associated with the supply and demand of overtaking opportunities. The demand often cannot be met and vehicles are forced to travel at the speed of the slowest vehicle until a passing opportunity presents itself.

The literature is summarized in another study that suggests that speed-volume effects for one vehicle type depend on the free speeds of other vehicle types (*20*). It goes on to suggest the use of a three-zone speed-volume relationship such as is shown in Figure 3. Below a certain volume, *Q0*, there are no interaction effects. Between this volume and the practical capacity, *QCAP*, speeds decrease as a result of the interaction effects. At the practical capacity, all vehicles travel at the speed of the slowest type. Beyond the practical capacity, the speeds decrease rapidly to a minimum jam speed, which is reached at maximum congestion. This process can be mathematically expressed as follows (*20*):

$$SQ_i = S_i \qquad QHR \leq Q0 \qquad (7)$$

$$SQ_i = S_i - (SCAP)(QHR - Q0)/(QCAP - Q0) \qquad Q0 < QHR \leq QCAP \qquad (8)$$

$$SQ_i = SCAP - (SCAP - SJAM)(QHR - QCAP)/(QJAM - QCAP) \qquad QCAP < QHR \leq QJAM \qquad (9)$$

where

S_i = free speed of vehicle type *i* in km/hr,
SQ_i = volume-influenced speed of vehicle type *i* in km/hr,
$SCAP$ = speed at practical capacity in km/hr,
$SJAM$ = minimum jam speed in km/hr,
QHR = hourly traffic volume in passenger car equivalents (PCE)/hr,
$Q0$ = base volume level in PCE/hr,
$QCAP$ = practical capacity in PCE/hr, and
$QJAM$ = maximum volume in PCE/hr.

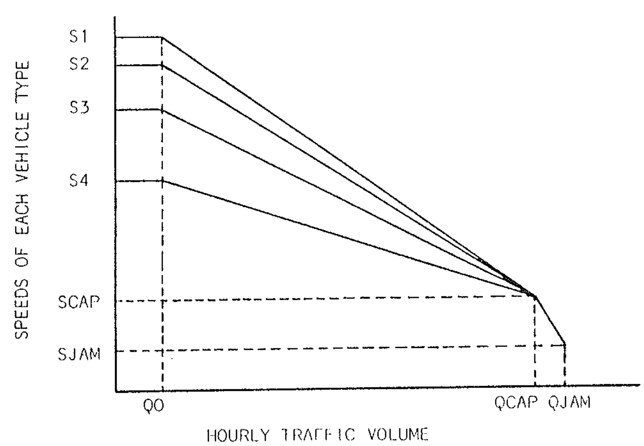

FIGURE 3 **Three-zone speed-volume model.**

It is recommended that *SCAP* be quantified as the 15th percentile speed of the slowest vehicle (*20*). Because speeds generally are normally distributed, this value can be approximated by the mean-minus-one standard deviation. Values for the coefficient of variation of vehicle speeds (defined as the mean divided by the standard deviation) that are based on New Zealand studies are given in another study (*24*). The speed at capacity is therefore calculated as follows:

$$SCAP = \min[S_i(1 - COV_i)] \qquad (10)$$

where

COV_i = the coefficient of variation of speeds for type *i* vehicles.

The recommended values for *Q0*, *QCAP*, *QJAM*, and *SJAM* are given in the following table.

Parameter	*Value*	*Units*
Q0	100	PCE/hr
QMAX	2,500	PCE/hr
QJAM	3,125	PCE/hr
SJAM	8	km/hr

These values are expressed in terms of PCE/hr; it is therefore necessary to establish equivalency factors for the other vehicle types. A range of values from different studies is provided elsewhere (*20*). It must be emphasized, however, that because this model is not based on empirical observations, the values in the preceding table are only estimates.

In order to use the speed-volume modeling technique outlined earlier, it is necessary to know the hourly distribution of traffic volume. It has been found that for all rural roads in New Zealand, the hourly distribution is bimodal of the form shown in Figure 4 (*25, 26*). A typical distribution was selected that was based on a consideration of distributions from 11 sites (*1*). For modeling purposes it was assumed that there were five significant ranges of volume levels. These ranges and the number of hours that they can be anticipated to occur each year are given in the following table.

Volumes as Percentage of AADT		
Range	*Mean*	*Number of Hrs/Yr*
0-1	0.50	2,294
1-5	2.58	2,532
5-9	6.87	3,524
9-11	9.80	355
>11	11.66	51

The NZVOC2 model therefore divides an estimate of the annual average daily traffic (AADT) into five representative volumes, establishes the appropriate speed for each volume on the basis of the volume and mean free speed, calculates the vehicle operating costs, and then aggregates these costs to obtain the total annual cost.

EXAMPLES OF NZVOC2 MODEL PREDICTIONS

The NZVOC2 model can be used to provide standard tables of vehicle operating costs or to analyze individual segments of roads. The model provides two types of standard tabulated cost estimates: running costs and roughness-related costs. The former are composed of the costs that result from fuel, tires, oil, repairs, labor, and that portion of depreciation that results from

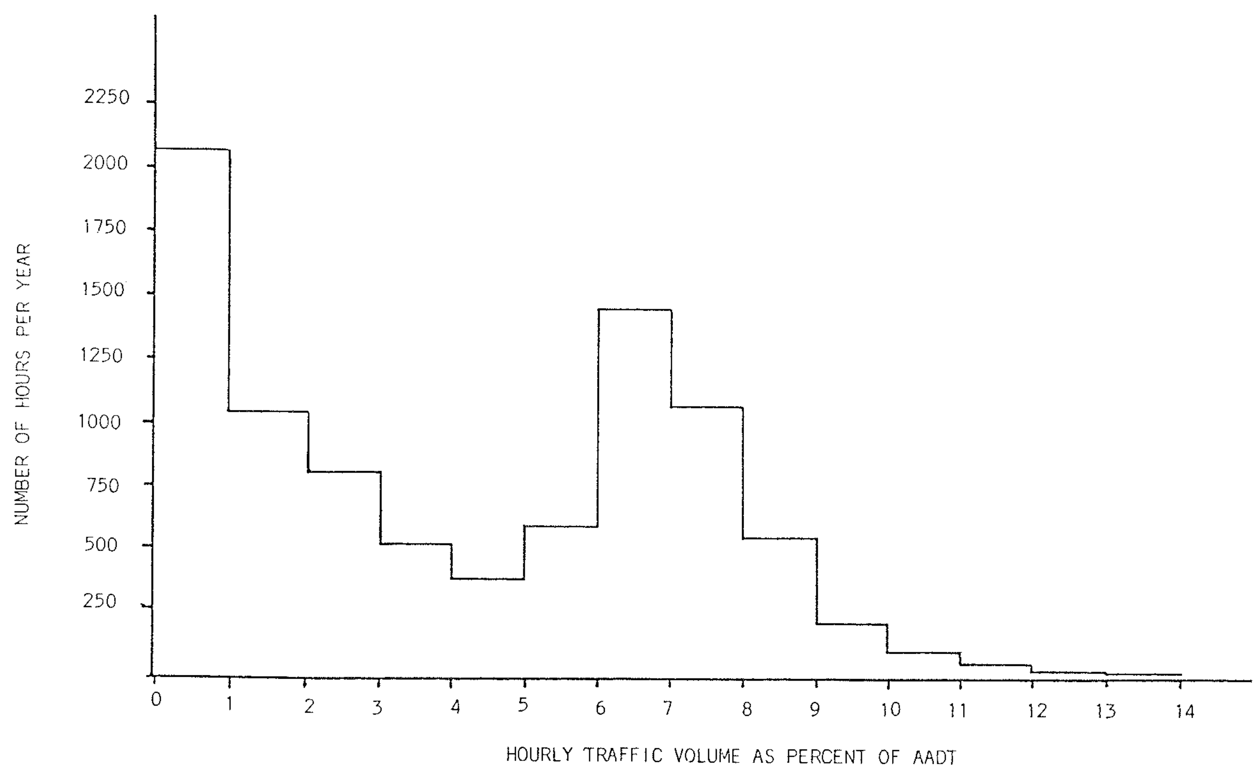

FIGURE 4 Hourly distribution of traffic volume.

vehicle use. The latter constitute the additional costs that result from changing roughness levels. Each of these costs is discussed individually.

Five significant independent variables were used in the calculation of the running costs. In increasing order of importance they are altitude, curvature, roughness, gradient, and speed.

The altitude affects the operating costs through its effects on the mass density of air. It has a very minor impact that amounts to less than 1 percent over the entire range of altitudes in New Zealand. Because of this insensitivity, all costs were calculated using a value of 10 m above sea level for the altitude.

The main impact of curvature on operating costs is through its effect on vehicle speeds. In terms of a direct effect on operating costs, only commercial vehicle tire consumption is affected by curvature. The running costs were calculated using a constant value of 10 degrees/km for curvature.

Roughness is an important variable, as evidenced by its inclusion in each of the HDM-III model relationships. Unfortunately, the Australian Road Research Board (ARRB) was concentrating on urban traffic management; therefore, surface roughness is not incorporated in the ARRB fuel consumption model. In calculating the running costs, it was decided to eliminate the roughness effects by having all costs calculated at a roughness of zero National Association of Australian State Road Authorities (NAASRA) counts/km. Separate roughness costs could then be added to these base costs to establish the total vehicle operating costs. Because the HDM-III model uses the QI roughness measure, whereas in New Zealand roughness is measured using a NAASRA Meter, it was necessary to convert NAASRA counts to QI counts (*27*). This was done using the following approximate relationship (*17*).

$$QI = (46.7 + NAASRA)/2.761 \tag{11}$$

where

$NAASRA$ = roughness in NAASRA counts/km, and
QI = roughness in QI counts/km.

It must be stressed that this is a very approximate relationship based on estimates of the relationship between the NAASRA Meter and the TRRL Bump Integrator and the Bump Integrator and the QI measure. The Ministry of Works and Development undertook field studies to quantify a more exact relationship; however, there were errors in the data. It is hoped that these errors will be resolved and that a more accurate relationship will be available in the near future.

The additional roughness costs were established by first calculating a base operating cost at zero roughness. Because the effect of roughness on commercial vehicle fuel and tire costs is itself affected by vehicle speed, the base costs were calculated over a range of speeds. The additional costs of operating on roads with roughness levels above zero were determined by calculating the average operating costs at each roughness level and subtracting the base roughness cost. The additional roughness costs for each class of representative vehicle are depicted in Figure 5 (*4*).

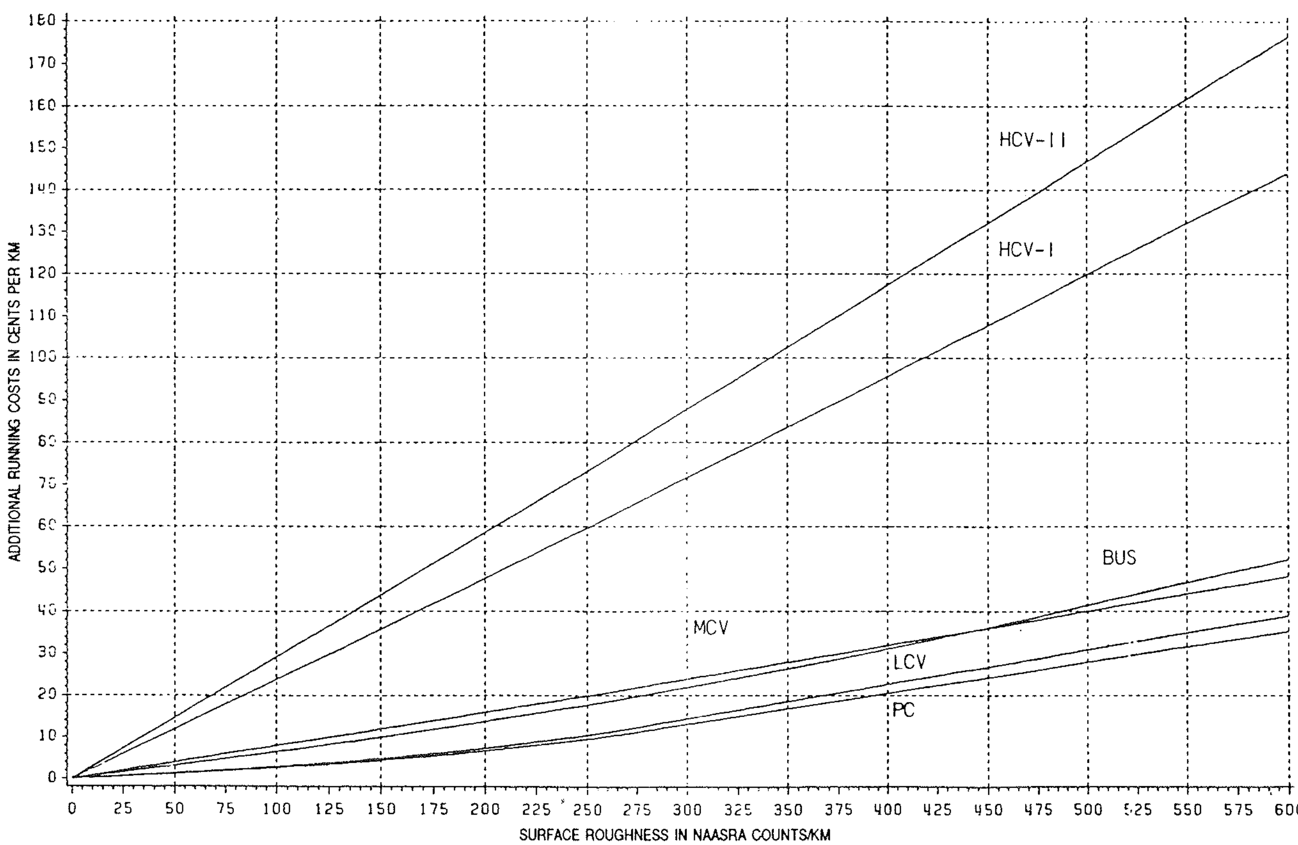

FIGURE 5 Additional running costs as a result of road roughness.

The running costs were calculated for a range of speeds from 10 to 120 km/hr operating on roads with gradients from -10 percent to +10 percent. As was discussed earlier, these costs were calculated using the following values for the other independent variables: altitude—10 m above sea level, curvature—10°/km, and roughness—zero NAASRA counts/km. In addition, the standardized speed distributions discussed earlier were used for each of the vehicle classes.

The NZVOC2 model predictions for rural passenger cars are depicted in Figure 6 (*4*). Because the ARRB model is linear in regard to gradient, the curves are fully symmetrical. The same does not apply to commercial vehicles, as shown in Figures 7 and 8, in which the running costs for the commercial vehicle reach a minimum at approximately -3 percent grade before increasing again (*4*).

The costs increase again because of the mechanistic commercial vehicle tire consumption model, which predicts that the tire consumption will be at a minimum when the sum of the forces that are opposing motion is at a minimum. Beyond this point, which occurs when the gravitational acceleration is equal to the rolling and aerodynamic resistances, the tire consumption can be anticipated to increase.

A complete set of operating cost tables and curves is presented in another publication (*4*). In addition to costs for individual vehicles, this publication contains cost estimates for standard mixes of traffic. This simplifies the manual appraisal process, because an analyst only has to refer to a single table or curve to estimate the costs. The NZVOC2 model is designed to prepare cost estimates for mixes of traffic; all that is required is the specification of the distribution of vehicle classes in the traffic stream.

The NZVOC2 model has not yet been used to independently evaluate single segments of highway, although it has been used in a research role to estimate the total road transport costs for New Zealand (*1*). It is anticipated that further developments of the model will be undertaken, specifically in the form of improved error reporting facilities, and that the model will be eventually released for use as an economic appraisal tool to supplement the manual method. Copies of the model that are suitable for running on an IBM personal computer are available by sending a floppy disk to The Technical Secretary, Administration Committee, National Roads Board, P.O. Box 12-041, Wellington North, New Zealand.

There will be a small charge to cover documentation and postage costs. Any requests for the Technical Recommendation for the Economic Appraisal of Roading Improvement Projects may also be sent to this address (*4*).

CONCLUSIONS

The New Zealand Vehicle Operation Model, NZVOC2, was developed specifically to meet New Zealand's requirements for an easy-to-use model that could be employed to estimate vehicle operating costs for use in highway economic appraisals.

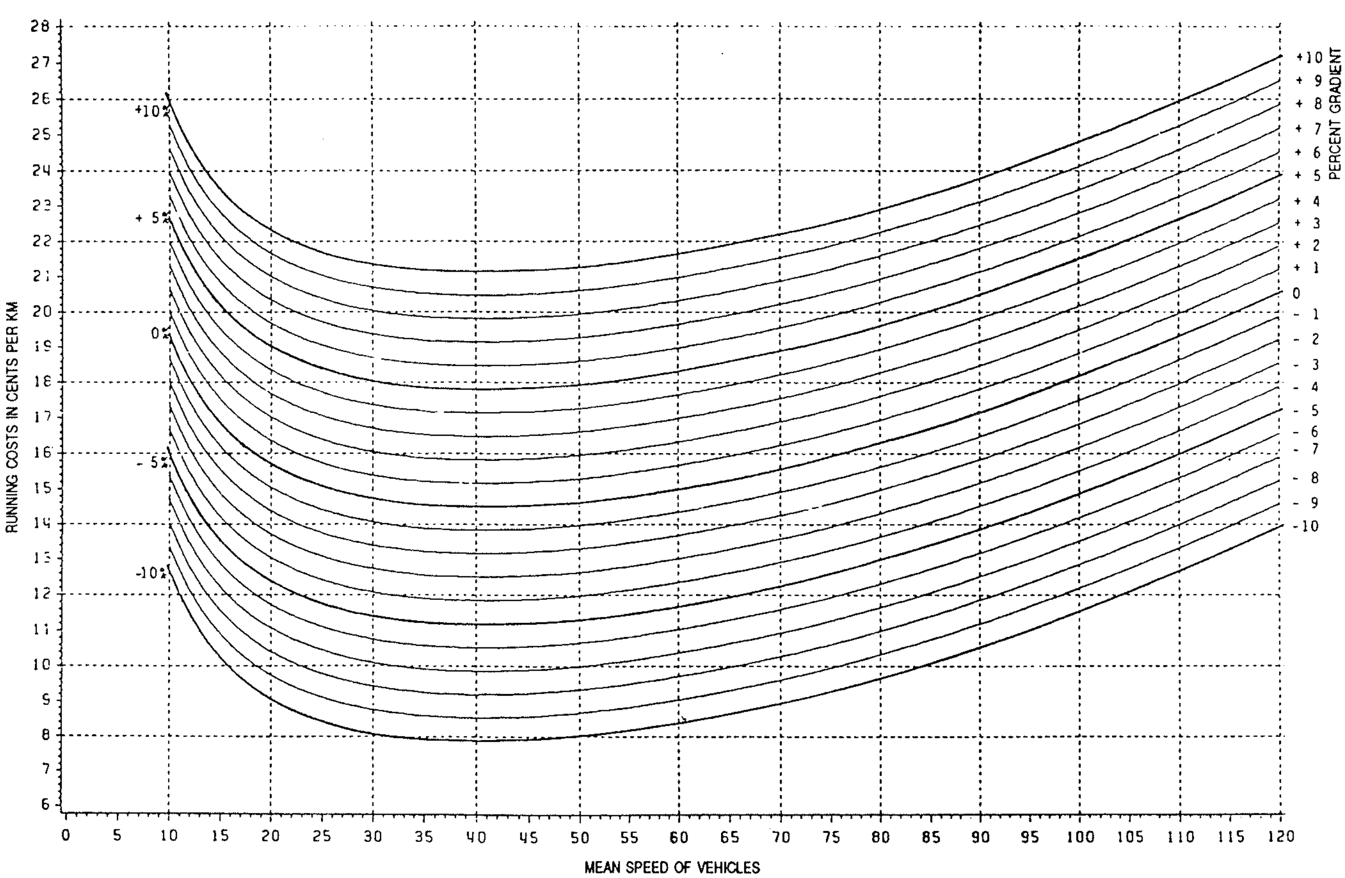

FIGURE 6 Rural passenger car running costs.

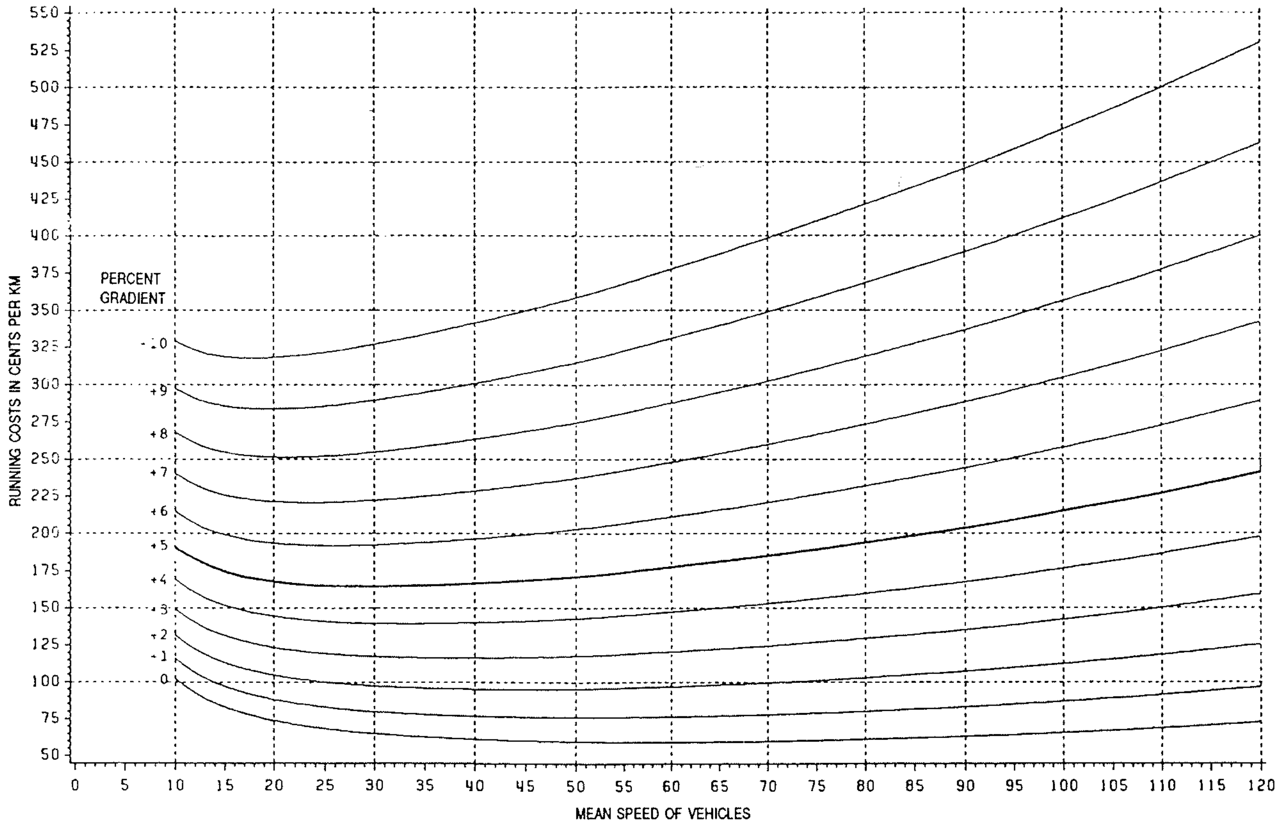

FIGURE 7 Heavy commercial vehicle (HCV-II) running costs on positive grades.

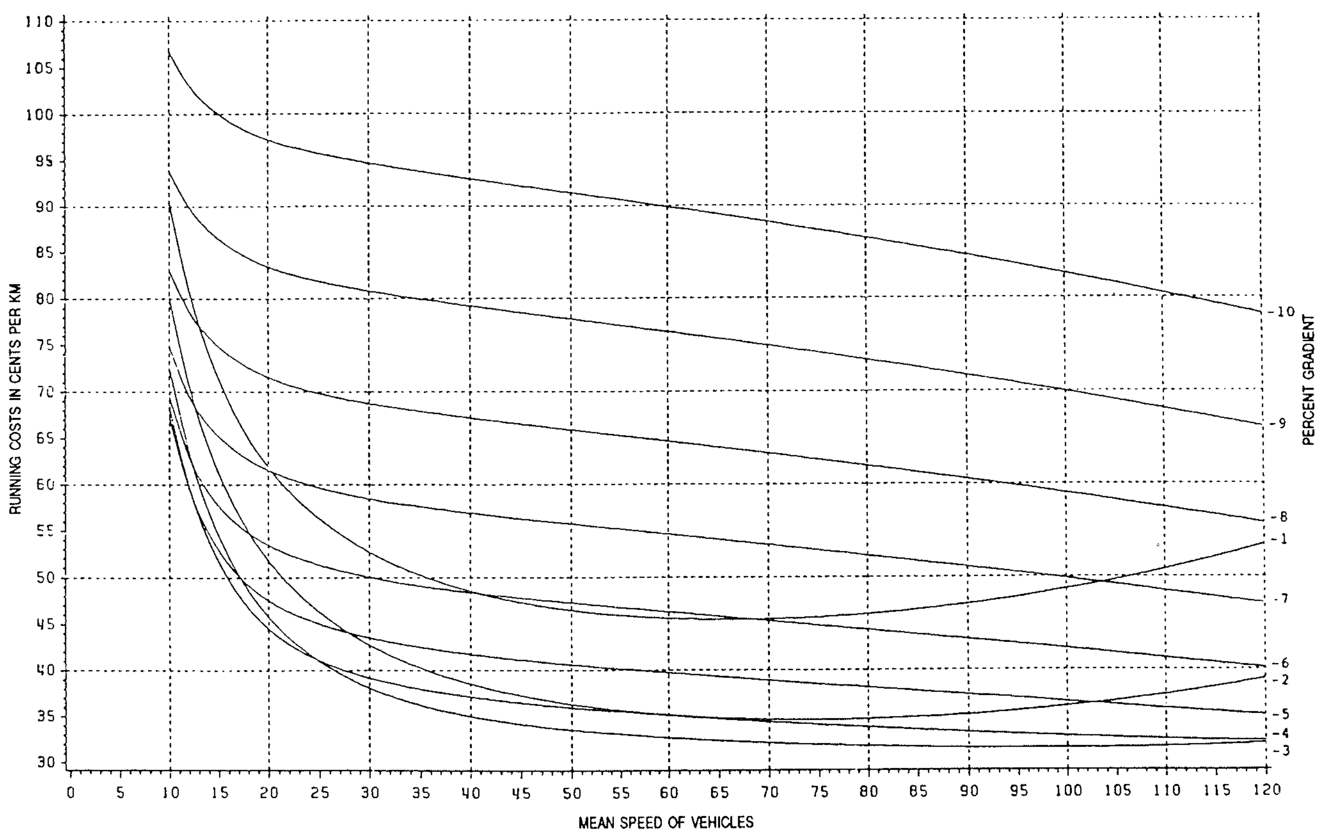

FIGURE 8 Heavy commercial vehicle (HCV-II) running costs on negative grades.

The relationships used in the model are primarily based on the World Bank's HDM-III model; passenger car and light commercial vehicle fuel consumption are predicted by use of Australian Road Research Board models. These overseas relationships were selected after their relevance to New Zealand vehicles and operating conditions was considered. Depreciation costs are based on the results of studies that were conducted within New Zealand and they successfully differentiate between the use- and age-related components of depreciation.

All countries that are considering the adoption of operating cost relationships that are not based on local research should undertake an evaluation similar to what has been done in New Zealand. Only then can it be ensured that the predictions are meaningful and relevant to the country in question. It is important that these predictions be accurate; given the nature of investments in low-volume roads, this is the only way to ensure the optimal allocation of funds.

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REFERENCES

1. W. D. Scott Deloitte Ltd. *An Investigation Into the Road Research Unit's Budget Level and Priorities—Phase I: The New Zealand Road User Costs.* Report to the National Roads Board, Auckland, 1986.
2. B. E. Cox. *A Review of the Application of Economic Appraisals to Highway Decision Making.* Presented at the New Zealand Roading Symposium, Wellington, 1979.
3. D. W. Beatty and N. S. L. Read. *Economic Appraisals of Highway Projects.* Presented at the New Zealand Roading Symposium, Wellington, 1971.
4. I. H. Bone. The Economic Appraisal of Roading Improvement Projects. RRU Technical Recommendation TR9. National Roads Board, Wellington, New Zealand, 1986.
5. R. Winfrey. *Economic Analysis for Highways.* International Textbook Co., Scranton, Pa., 1969.
6. C. G. Harral, and S. K. Agarwal. *Special Report 160: Highway Design Standards Study.* TRB, National Research Council, Washington, D.C., 1975.
7. P. J. Claffey. *NCHRP Report 111: Running Costs of Motor Vehicles as Affected by Road Design and Traffic.* HRB, National Research Council, Washington, D.C., 1971.
8. H. Hide et al. *The Kenya Road Transport Cost Study: Research on Vehicle Operating Costs.* TRRL Report LR 672. Department of the Environment, Transport and Road Research Laboratory, Crowthorne, England, 1975.
9. J. W. Hodges et al. *The Kenya Road Transport Study: Research on Road Deterioration.* TRRL Report LR 673. Department of the Environment, Transport and Road Research Laboratory, Crowthorne, England, 1981.
10. H. Hide. *Vehicle Operating Costs in the Caribbean: Results of a Survey of Vehicle Operators.* TRRL Report LR 1031. Department of the Environment, Transport and Road Research Laboratory, Crowthorne, England, 1981.
11. G. Morosiuk and S. W. Abaynayaka. *Vehicle Operating Costs in the Caribbean: An Experimental Study of Vehicle Performance.* TRRL Report LR 1056. Department of the Environment, Transport and Road Research Laboratory, Crowthorne, England, 1981.
12. Central Road Research Institute. *Road User Cost Study in India.* 5 vol. Final Report, New Delhi, India, 1982.
13. Empresa Brasileira de Planejamento de Transportes (GEIPOT). *Research on the Interrelationships Between Costs of Highway Construction Maintenance and Utilization.* 12 vol. Final Report on Brazil-UNDP Highway Research Project, Brasilia, 1982.
14. T. Watanatada et al. *The Highway Design and Maintenance Standards Model (HDM-III): Users Guide and Model Description.* Transportation Department, The World Bank, Washington, D.C., 1985.
15. C. R. Bennett. *A Highway Economic Evaluation Model for New Zealand.* School of Engineering Report 368. Department of Civil Engineering, University of Auckland, 1985.
16. W. D. Scott Deloitte Ltd. *A Guide to the Use of the NZVOC2 Model.* Report to the National Roads Board, Auckland, 1986.
17. W. D. Scott Deloitte Ltd. *The New Zealand Vehicle Operating Costs Model—NZVOC2.* Report to the National Roads Board, Auckland, 1986.
18. W. D. Scott Deloitte Ltd. *Unit Costs for Use in the NZVOC2 Model.* Report to the National Roads Board, Auckland, New Zealand, 1986.
19. T. Watanatada et al. *Models for Predicting Vehicle Speeds and Operating Costs Based on Mechanistic Principles: Theory and Quantification.* Internal Report. Transportation Department, The World Bank, Washington, D.C., 1985.
20. C. J. Hoban. *Appropriate Geometric Standards for Rural Roads.* Internal Report. Transportation Department, The World Bank, Washington, D.C., 1986.
21. D. Bowyer et al. *A Guide to Fuel Consumption Analyses for Urban Traffic Management.* Report AIR 390-9. Australian Road Research Board, Nunawading, 1984.
22. P. G. Maloney. *Vehicle Repairs and Maintenance Costs: A Methodology and Literature Review.* Internal Report. Ministry of Transport Economics Division, Wellington, New Zealand, 1982.
23. SAS Institute, Inc. *SAS User's Guide.* Carey, North Carolina, 1982.
24. C. R. Bennett. *Vehicle Speeds on Rural Roads in New Zealand.* Roading Directorate Report RRS-007. Ministry of Works and Development, Wellington, 1985.
25. C. R. Bennett. *The Representation of Traffic Volume Data for Use in Economic Analyses.* Roading Directorate Report RRS-006. Ministry of Works and Development, Wellington, New Zealand, 1985.
26. C. R. Bennett. The Representation of Traffic Volume Data for Use in Economic Analyses. *Proc., 13th ARRB/5th REAA Adelaide Conference*, Australian Road Research Board, Nunawading, 1986.
27. National Association of Australian State Roading Authorities. *Standard Operating Instructions for the NAASRA Roughness Meter and Guide for the PSR of Road Pavement.* Technical Report. NAASRA, Sydney, 1981.