A TOTAL COST APPROACH TO FLEET REPLACEMENT: THE TRANSPERTH BUS REPLACEMENT MODEL

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ABSTRACT

This paper describes a method of determining the annual number of replacement buses to be purchased which is optimal in the sense of minimising the net present value of capital and operating costs for the whole Transperth fleet over a suitable time horizon.

The model takes into account the effect of the introduction of new buses on the annual distance performed by all existing buses, and hence their operating costs.

The micro computer implementation of the model allows the user to interactively examine various replacement policies and to gradually home in on the point at which the trade off between lower operating costs and higher capital costs results in the optimal replacement policy. The sensitivity of the results to variations in key parameters such as bus unit costs, interest rates and inflation can also be examined.

TOTAL COST APPROACH TO FLEET REPLACEMENT

1. INTRODUCTION

In the past, Transperth's approach to replacement of buses has been to let a single contract for the required number once approval has been gained from the government.

Transperth is presently seeking to implement a "rolling" procurement program. Under this program, Transperth will commit to buy a certain number of buses every year for, say, 5 years, with some provision for adjustment as anticpated requirements change.

The perceived benefits of this approach include:

1. Reduction in the unit costs of buses by eliminating the set up costs incurred by the body builders. Hitherto, due to the lapse of time between the termination of one contract and the commencement of another, the body builders have needed to obtain premises, equip themselves with tools and train a workforce at the commencement of each contract.

2. Elimination of quality problems previously incurred on the initial buses of each contract.

3. In the long term, a "leveling" of the age distribution of buses in the fleet, ie, the bus fleet, will eventually attain a state where the number of buses in each age group is approximately the same.

In order to realise these benefits, Transperth requires a method of selecting the "optimum" number of buses to be replaced in any future year.

Obviously, Transperth incurs a direct cost in the purchase of buses, which increases as the annual procurement of replacement buses rises. Up to a certain level, these costs can be offset by quantifiable savings resulting from a reduction in the maintenance costs for older buses.

In the past, Transperth has made use of a number of techniques which focus on the problem of determining the optimal service life of a single bus. This paper argues that a more consistent approach is to look at the effect of alternative replacement policies on the costs of the whole fleet.

2. LIFE CYCLE APPROACHES TO BUS COSTING

A number of approaches exist to determining the service life of a piece of equipment. Some of these are briefly discussed below:

Machinery and Allied Products Institute (MAPI) Method

This method (Schwan,1963), determines the optimum service life as the minimum of the function:

$$C/K + c(K) - c(0) \qquad \dots (1)$$

where:

C   = capital cost of a new machine
K   = service life of a machine
c(K) = operating cost of a machine in year K of its life
c(0) = operating cost of a new machine

The first term is the capital cost component charged to each year of the life of the machine. The essential argument of the MAPI method is that the optimum time to replace a machine is the point at which (1) is a minimum, ie the point at which the decline in capital charges is overtaken by an increase in operating costs.

Net Present Value (NPV) Methods

These methods seek to establish the service life at which the present value of owning and operating a bus is a minimum.

Over K years, the NPV of owning and operating a bus is:

$$NPV(K) = C + \sum_{k=1}^{K} \frac{c(k)}{(1+r)^k} \qquad \dots (2)$$

where r is the discount rate.

NPV methods are designed to compare alternative investment projects. To ensure consistency, projects must be compared over the same service life, a condition which is clearly not achieved by simply comparing NPVs calculated over one life cycle.

One method of achieving this is the method of "infinite replication

at constant scale" (Copeland and Weston,1979).

As the name suggests, this method assumes that, at the completion of a project, it is immediately replicated, with this replication continuing forever. This assumption can be seen to correspond rather well to the situation with regard to replacement of buses.

The infinitely replicated NPV of costs for a bus with a service life of K years is then:

$$RNPV(n) = \sum_{n=0}^{\infty} \frac{NPV(K)}{(1+r)^{nK}} \quad \quad \dots (3)$$

The optimum service life can then be established by comparing the replicated NPVs for each of a number of alternative service lives.

Discounted Weighted Average Cost (DWAC) Techniques

These methods (Simmons, 1982), developed by the W.A Department of Transport, represent another way of ensuring the comparability of results obtained by Net Present Value Methods. The Average Annual Cycle Cost (AACC) per kilometer is calculated as:

$$AACC(K) = NPV(K)/PVD(K) \quad \quad \dots (4)$$

The "Present Value of Distance" is defined as:

$$PVD(K) = C + \sum_{k=1}^{K} \frac{x(k)}{(1+r)^{k}} \quad \quad \dots (5)$$

where x(k) is the distance covered by a bus in year k of its life. The AACC is a weighted measure of operating costs, expressed in \$/km, over the service life of the bus; the optimal service life is that for which the AACC is a minimum.

Problems with Life Cycle Costing Methods

The successful application of these techniques to the service life problem relies on accurate calculation of the operating costs in-

curred under various service life regimes.

To the extent bus operating costs are related to distance traveled, this translates to the problem of determining the effect of a change in service life on annual distance traveled.

At present, the newest buses in the Transperth fleet are heavily utilised in order to take maximum advantage of warranties and to present the most attractive buses to off peak travelers. These buses run annual distances on the order of 80-100 000 km. The oldest buses, which typically operate only in the peak periods, cover 15-25 000 km per year. Between these extremes, the annual distances covered by buses is a decreasing function of age.

In this situation, determining the effect of a change in service life on annual distance traveled is clearly not a trivial task, since:

1.   The total distance run by a bus over its service life can be expected to be a function of that life;

2.   The fleet as a whole is constrained to perform a certain total annual distance in meeting the demand for public transport.

A more serious problem is that the old bus which is retired and the new bus which replaces it are not equivalent because of the difference in annual distances run. The replacement of a group of old buses has an impact on the annual distances run by all remaining buses in the fleet, and hence on the annual operating costs of these buses. The change in the operating costs of these buses must be included in any realistic replacement calculation.

In a fleet consisting of a variety of different bus types, it is difficult to see how this can be done.

3.   AN ALTERNATIVE APPROACH

An alternative approach to the problem is to study the effect of various bus replacement policies on the total costs of owning and operating the fleet. This is an approach which recognises that Transperth is a "going concern" and that buses are, to say the least, an essential part of its stock in trade.

In this light, the cost of replacement buses is a recurrent expenditure, rather than an isolated capital outlay made to take advantage of a passing investment opportunity.

Transperth's annual costs for owning and operating the bus fleet is

the sum of:

1. Expenditure on replacement buses;

2. Costs of operating the existing buses in the fleet.

The optimal replacement policy is that which minimises, over a suitable forecast horizon, the total discounted cost of replacing and operating buses to meet a specified demand for public transport.

The bus replacement model which implements this approach has two major components:

1. A Distance Assignment algorithm which assigns annual distances to buses as a function of their age relative to other buses in the fleet in such a way as to ensure that the total distance traveled by all buses in the fleet is consistent with the total transport task required of the fleet.

2. A Bus Cost Model which expresses the total annual cost of owning and operating a bus in terms of its initial capital cost, its age, its annual distance run (derived from the distance assignment algorithm) and its total distance run.

Using these components, the replacement model builds up a history of distance traveled for each bus in the fleet, as well as details of total costs to Transperth.

It should be emphasized that, in its present form, the replacement model is <u>not</u> an optimisation model. The user is able to interactively specify various bus replacement options, evaluate the total discounted costs and hence home in on the optimal solution.

4. DISTANCE ASSIGNMENT MODEL

In order to compute the fleet operating costs in any given year, it is necessary to predict the distances run by each bus in the fleet in that year.

The technique used to assign distances to buses must conform to two broad constraints:

1. The total distance traveled by all buses in the fleet in a given year must add back to the total distance expected to be performed by the fleet in meeting demand for public transport in that year.

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2.   The distance assigned to a bus must be reasonable in terms of
      maintainable average speeds and downtime required for mainte-
      nance of that bus.

The basis of the assignment technique comes from an analysis of the
distances covered by buses in the Transperth fleet. If buses in the
existing fleet are ranked in order of age and the distances covered
by each bus are plotted, a curve as shown in Fig. 1 results. This
curve shows that annual distance covered generally falls off with
age.

An "idealised" version of this curve in shown on Fig. 2. This curve
has the following properties:

1.   The areas under the actual and idealised curves (which is the
      total fleet annual distance) are the same;

2.   The curves apply to the same number of buses;

3.   The shapes of the curves are "similar". In particular, the
      annual distances run by buses as they age are roughly equiva-
      lent.

The "load" curve is described by the discrete function:

$d(i,t) =$ distance (km) to be covered by the ith ranked bus in
              year t

where the rank ordering is such that:

$$i > j \longrightarrow d(i,t) \leqslant d(j,t)$$

In other words, the higher the rank ordering of a bus, the less the
distance traveled in a year. The time dependence emphasises that the
shape of this load curve, as well as the number of buses, can change
from year to year.

The load curve so defined can be used to determine the distance
traveled by any bus in the fleet in a given year:

1.   Rank buses according to the distance to be covered in the
      course of a year, with those buses required to cover the
      greatest distance at the bottom of the list and those to cover
      the least distance at the top.

      Generally, this ranking will closely match the age ordering of

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Fig 1: Annual Distances by Bus Groups

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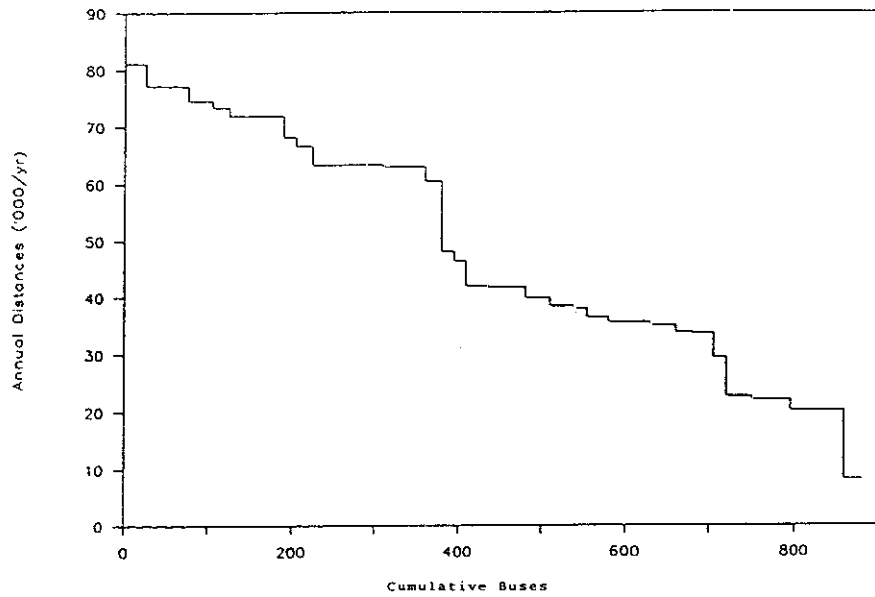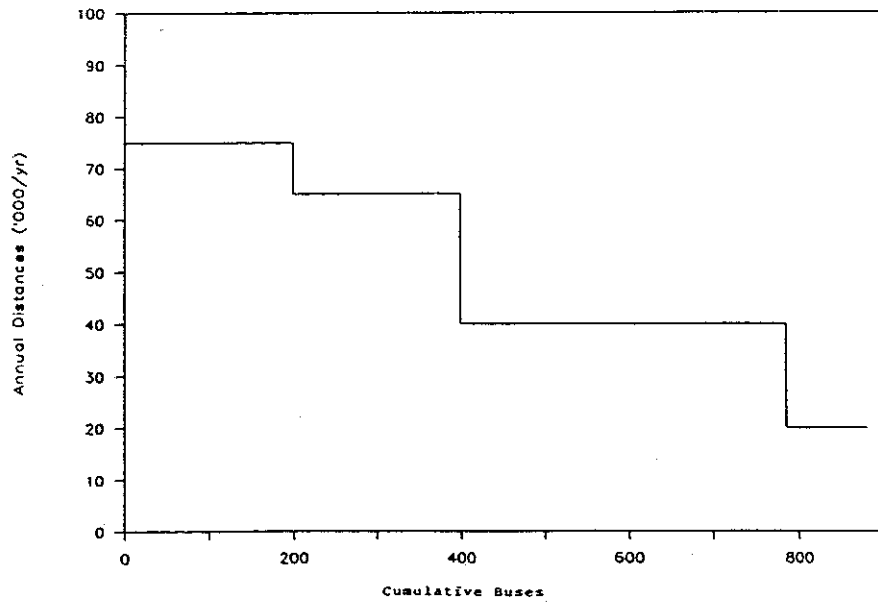
Fig 2 : "Idealised" Bus Group Distances

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buses in the fleet (from newest to oldest).

2.   The distance to be covered by each bus in the group can then
      be read off the idealised distance curve.

Subject to the assumption that the rank ordering of buses does not
change (or changes in a known manner) in the course of a simulation
run, this method allows the annual distance covered by a bus as it
ages to be tracked.

Replacement buses enter at the bottom of the ranking list, pushing
existing buses up the list; old buses are retired from the top of
the ranking list. In each successive year, as replacement buses
enter the fleet, the distance to be covered by each bus decreases as
its rank increases.

The technique is readily adapted to changes in the shape of the load
curve from year to year and/or to an increase or decrease in the
number of buses in the fleet.

For purposes of computation, it is more convenient to deal with
groups of buses of the same make, model and age.

The position of bus group g in the fleet rank ordering in year t is
defined by:

$N(g,t)$ = number of buses in group g in year t
$R(g,t)$ = ranking of the lowest ranked bus in group g in year t.

Buses in the same group are assumed to be ranked as a contiguous
group. The average distance covered by buses in group g in year t is
then given by:

$$x(g,t) = (1/N(g,t)) * \sum_{i=R(g,t)}^{R(g,t)+N(g,t)-1} d(i,t) \qquad \ldots(6)$$

Also, let:

$X(g,t)$ =   total distance (km) covered by buses in group g up to
              the end of year t

Then, the <u>total</u> distance run by buses in group g up to the end of year t can be determined from:

$$X(g,t) = X(g,t-1) + x(g,t) \qquad \ldots (7)$$

If the number of replacement buses purchased in year t is R(t), then the change in the ranking of the lowest ranked in group g is:

$$R(g,t) = R(t) + R(g,t-1) \qquad \ldots (8)$$

5. BUS COST MODEL

The cost models take into account the following factors:

1. Capital cost;
2. Operating costs related to total distance run;
3. Operating costs related to annual distance run;
4. Age of bus;

Capital Costs

The initial purchase price of a bus of a given type is assumed known. Within the model, this cost is converted to the annual series of outlays which is equivalent to the initial cost over a specified cost recovery life at a specified interest rate.

This cost is charged to the bus for each year of this recovery period, regardless of whether the bus is actually retired before this number of years elapses; if the bus remains in the fleet for a number of years longer than the recovery period, no capital charge is made for these latter years.

The capital costs are charged only for years within the time horizon under study; this represents a solution to the terminal valuation problem.

Let:

L = number of years over which the capital cost of the bus is to be recovered (capital cost recovery life).
P = value of the series of L equal repayments which is equivalent to the initial cost of the bus.
C = equivalent annual cost

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Then:

$$C = P * \sum_{k=1}^{L} \frac{1}{(1+r)^k} \qquad \cdots (9)$$

Hence:

$$P = C * F(r,L) \qquad \cdots (10)$$

where:

$$F(r,L) = \frac{r * (1+r)^L}{(1+r)^L - 1} \qquad \cdots (11)$$

Let:

$E(g)$ = year in which buses in group g enter the fleet.

Then the capital cost to be charged to buses in group g in year t of the simulation run is:

$$CAP(g,t) = N(g,E(g)) * C(g) * F(r,L(g)) \qquad E(g) \leqslant t \leqslant E(g)+L(g)-1$$

$$= 0 \qquad \text{otherwise} \qquad \cdots (12)$$

Note that capital costs are always charged to the number of buses initially in the fleet.

Costs of Mechanical Overhauls

At regular increments of total distance run, each bus is subject to a major mechanical overhaul.

If a bus crosses the threshold for such an overhaul during a year of the simulation run, the cost of this overhaul is charged to the bus during that year.

Let:

$M(g,D)$ =   cost of a major mechanical overhaul for a bus in group g incurred after the bus has traveled a total distance of D km.

Then, the cost of mechanical overhauls incurred in year t of the simulation by buses in group g is:

$$MECH(g,t) = N(g,t) * \sum_{d\ :\ X(g,t-1)\ <\ D\ \leqslant\ X(g,t)} M(g,d) \qquad \dots (13)$$

Running Costs

A bus in service incurs costs on a continuous basis as a result of fuel, oil and tyre consumption as well as regular daily inspections and frequent minor servicing (at about 5 000 km intervals). These costs are most conveniently represented as an operating cost in $/km.

A bus also incurs lump sum costs at irregular intervals as a result of breakdown recovery, rectification of major mechanical failures and repair of accident damage. Because of the unpredictable intervals at which these costs are incurred, and their variable magnitude, it has been found useful to represent them also as a $/km cost averaged over all buses in the group.

In general, these running costs are found to increase with the total distance run by a bus. Hence, the total running costs incurred in year t by buses in group g is:

$$RUN(g,t) = N(g,t) * \int_{X(g,t-1)}^{X(g,t)} RC(g,X)\ dX \qquad \dots (14)$$

where:

RC(g,X) =   running cost ($/km) of a bus in group g which has run a
            total distance of X km.

Body Overhauls

Deterioration of paintwork, body panels and interior fittings tends
to be a function of the age of the bus rather than accumulated
distance. Buses are periodically withdrawn from service for a body
overhaul in order to make good this deterioration.

The cost of such an overhaul is charged to the bus in the year in
which it occurs.

Let:

B(g,T) =   cost of major overhaul incurred in year T of the life of
            a bus in group g.

Then, the total cost of body overhauls incurred by buses in group g
in year t is:

BODY(g,t) = N(g,t) * B(g,t+1-E(g))

$$\ldots (15)$$

6.   THE COMPUTATIONAL PROCEDURE

The computational sequence which combines the above techniques is as
follows (see Fig. 3).

For each year of the run:

1.   Specify the required fleet size and the number of buses to be
     replaced.

2.   Determine the number of buses to be retired. This is given by
     the relationship:

     Buses Retired = Current Fleet Size
                      + Number of buses to be replaced
                      - Buses Required

FLEET TASK   MERIT LIST   DISTANCE BY BUS GROUPS

Operations of Bus Costing Model

TOTAL COST APPROACH TO FLEET REPLACEMENT

Figure 3
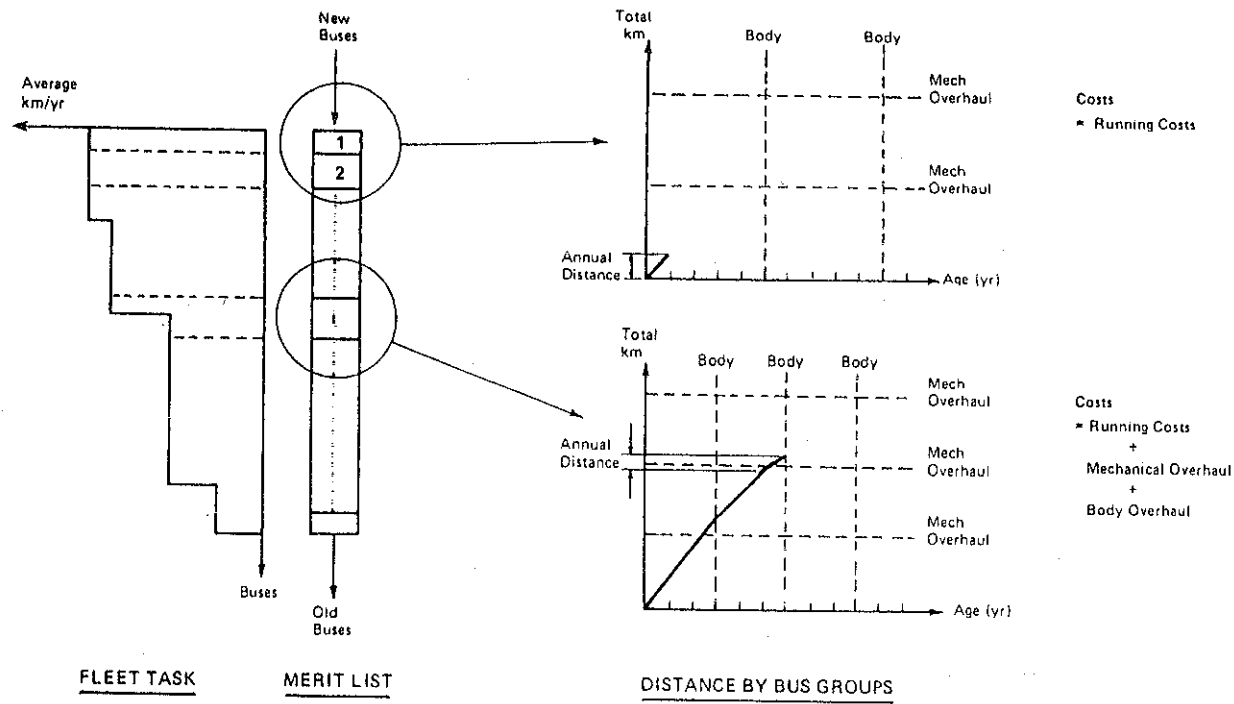
If the fleet is expanding, the right hand side of this expression may evaluate negative, in which case additional new buses must be purchased.

3. Remove buses to be retired from the top of the order ranking.

4. Add new buses to the bottom of the rank ordering and push existing buses up the rank ordering.

5. Assign annual distances for each bus group from the distance profile.

6. Update cumulative distances run by each bus group.

7. Compute the total of capital and operating costs for the year:

$$COST(t) = \sum_g (CAP(g,t) + MECH(g,t) + RUN(g,t) + BODY(g,t)) \qquad (16)$$

After costs for all years have been calculated, the Net Present Value of costs incurred over a simulation time horizon of H years is:

$$NPV = \sum_{t=1}^{H} \frac{COST(t)}{(1+r)^t} \qquad (17)$$

As pointed out above, the model is, at present, not an optimisation model. By systematically varying the number of each type of replacement buses purchased in each year of the simulation run, the user can "home in" on the optimal replacement policy, which minimises (17).

7.   IMPLEMENTATION ASPECTS

Language

The replacement model is implemented in compiled BASIC and runs on all types of IBM compatible PCs. In practice, the presence of an 80x87 coprocessor chip has been found to be very desirable.

Data Requirements and Management

The data required to completely describe the system for a simulation run falls into three categories:

1. A description of the initial state of the bus fleet, setting out the number buses in each group, the age and type of those buses and the total distance traveled prior to the start of the run.

2. Data enumerating the various parameters of the cost models for each type of bus in the fleet and/or being considered for purchase. Note that each bus group is of a given type; data need only be entered once for each type of bus, not for the group.

3. Details of the operating environment for each year of the simulation run, including the parameters of the load curve, inflation and interest rates and the numbers and types of buses whose purchase is committed.

A separate file is created for data in each category; the group of three files constitutes a "model" and can be accessed by a common name.

Data is entered and modified interactively, using a purpose built data editor. Fig.4 shows samples of the data screens for each of the files.

When the user attempts to save data entered into a data screen, the data is first checked for consistency and error messages are displayed if errors are detected. The program performs a number of other tasks, such as sorting time and distance based data into the correct order.

Calculations

When the model is run, the user is initially presented with a "Replacement Buses" screen which enables him or her to specify the number and make of replacement buses to be purchased in each year.

Fig 4 : Sample Data Entry Screens

(a) Fleet Initial State

```
------------------------------------------------------------------
=(v2.0)==ACDC.bs2=======================================[5]======
Bus Type            mercedes        R/A R    Code  ml

Capital Cost ('000$)  205           Service Life   25
                                    Value Factor   0.875

Low kms (% bus)      20             (%dist)        90
High kms (%bus)      20             (%dist)        110

   dist  -dock-  fixed  run  km/  fuel          ----body dock---
  '000km    $      $   c/km brkdn 1/100k        year day     $
   zero           100   4.2       39.43          10   40   71750
  300.0   6230    340   4.4       39.43          15   40   15375
  500.0           500   4.5       39.43          19   40   71750
  600.0   8100    820   4.6       39.43          24   40   15375
  900.0   8100   1780   4.9       39.43          29   40   71750
 1200.0   8100   2740   5.2       39.43
 1500.0   8100   3700   5.5       39.43

------------------------------------------------------------------
```

(b) Bus Data

```
------------------------------------------------------------------
=(v2.0)==ACDC.op2=======================================[5]======
Year 1988

Interest Rate (%) _____     % p.a. Inflators:  Capital  7.00
                                                Fuel     7.00
Peak Buses         762                          Running  7.00
                                                Docks    7.00
Running:     Rigid          Articulated
          Dist   Buses      Dist  Buses         --New Buses--
          96969    61       40000   41          Type   Number
          81065   128
          62889   244                            _      ___
          39931   252                            _      ___
          20882   137                            _      ___
                                                 _      ___

Discount Rate (%) _____    Fuel Cost (c/1)          47.85
                            Breakdown Cost (S/e)     117.0

------------------------------------------------------------------
```

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Fig 4 : Sample Data Entry Screens (cont)

(c) Operating Environment

```
------------------------------------------------------------------------
=(v2.0)==ACDC.fl2=========================================[5]======
Merit  Type   Age    ---Number----    -Dist%--      Dist   CapChg
                     Low  Med   Hi   Low   Hi               '000$
         1     al     1    4   11    4   100   100    23.3   _____
         2     rl     1   18   54   18   100   100    33.0   _____
         3     ml     1    9   27    9   100   100   109.2   _____
         4     bl     2    2    6    2    80   119   113.5   _____
         5     ml     2    4   11    4    72   127   174.5   _____
         6     ml     3    9   29    9    61   138   244.0   _____
         7     ml     4    4   12    4    89   110   312.2   _____
         8     al     7    4   14    4    73   126   382.0   _____
         9     bl     7    2    6    2    88   111   386.7   _____
        10     ml     5    8   24    8    64   135   390.9   _____
        11     ml     7   11   35   11    76   123   517.9   _____
        12     ml     8    9   28    9    77   122   528.3   _____
        13     ml     9    3   11    3    79   120   539.1   _____
        14     ml     9    4   10    4    81   118   600.0   _____
        15     ml     9    6   18    6    87   112   693.9   _____
        16     ml    12   12   38   12    84   115   698.1   _____
        17     ml    10    8   24    8    86   113   704.5   _____
        18     h2    13    3    7    3    92   107   750.0   _____
------------------------------------------------------------------------
```

When the number of buses is set, the model will carry out the calculation sequence described above, summarising the results on either the screen or a printer.

When the calculation is complete, the user can return to the "Replacement Buses" screen to perform another iteration.

Buses Approaching Retirement

In actual practice, the amount of maintenance performed on buses approaching retirement is limited to that necessary to keep them in service up to the point of retirement. The implementation of the model includes a number of user controlled options to prevent major maintenance costs being included in the calculation late in the life of a bus:

1. The model can "look ahead" to predict requirements for several years in advance of the current simulation year. This can be used to ensure that no major maintenance is carried out just prior to retirement.

2. This procedure can be extended to preferentially retire buses coming due for major maintenance.

3. An option exists to force retirement at some fixed maximum age.

8. DATA COLLECTION

The structure of the cost model, as outlined above, is fairly simple in principle. However, in practice, a number of problems are encountered in obtaining usable numerical values of the various costs.

1. Time series data on the historical operating costs of buses is not easy to obtain. Even where it is available, great difficulty is encountered in deflating the historical costs to obtain a series of constant dollar costs.

2. Record keeping systems tend not to break down costs incurred by the categories needed by a cost model. For work with the Transperth fleet, it was necessary to use regression analysis techniques to assign recorded costs to known major maintenance events, with running costs being computed as a residual.

3. Buses of a particular type tend to be of the same age, or nearly so. Even if it is possible to obtain good historical

data, this is of little use since few, if any, buses will exist to which it is applicable.

4. For predictive work of this type, it is necessary to extrapolate costs out into the future; this brings its own problems.

5. Operating costs due to maintenance procedures are not independent of replacement policy. A bus expected to remain in the fleet for 7 years, with a total distance run of, say, 500 000 km, will require less maintenance over that period than a bus expected to remain in service for 20 years and, say, 1 500 000 km.

These matters are dealt with in more detail in a companion paper (Ellison, 1989).

CONCLUSIONS

This paper has described a method of selecting an optimal replacement policy for buses based on the total costs of ownership and operation for a bus fleet.

The method shifts the focus of calculation from establishment of a fixed service life to that of timing bus replacement to minimise total costs and therefore bears more directly on the real issues involved in equipment replacement.

This method also has the following advantages:

1. Since the total distance traveled by the fleet in each year must be known, it is possible to ensure that the assumed fleet task is consistent with the actual task to be covered by the fleet in carrying out Transperth's transport task.

2. This annual distance can be varied with time, to take account of forecast growth or decline in the demand for public transport by bus.

3. The fact that the fleet contains a range of bus types with (in general) different operating cost characteristics, can be accommodated.

4. The factors considered in choosing the optimal replacement policy can be extended to include not only the annual number of buses to be replaced, but also the mix of bus types to be replaced.

ACKNOWLEDGEMENTS

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