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THE DESIGN OF NEW ROAD PAVEMENTS AND OF OVERLAYS: ESTIMATION OF COMMERCIAL TRAFFIC FLOWS

by

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CONTENTS

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ABSTRACT

In order to determine the required thickness of a new road pavement, or of an overlay on an existing road, the total commercial traffic in the nearside lane has to be estimated for the desired life of the pavement. For an overlay, the total commercial traffic since the last major strengthening is also needed. In the present Report, the estimates of traffic flow made in Road Note 29 for the design of pavements have been brought up to date and extended. A nomogram has been prepared to facilitate the estimation process. The computations have also been used to prepare a second nomogram to assist in estimating the past traffic that has been carried by a pavement.

1. INTRODUCTION

Road structures are progressively damaged by the passage of vehicles, particularly heavy commercial vehicles, and have finite lives, at the end of which reconstruction is necessary, although the life of a pavement can be extended by superposition of an overlay before irreparable damage has occurred.

The procedure for designing new road pavements is given in Road Note 29[1]. The Laboratory's method for designing bituminous overlays[2] is presently being revised[3] with new recommendations planned for publication in 1978.

The design of both new pavements and of overlays requires estimates of the total commercial traffic expected to use the nearside lane (the most heavily trafficked lane) of the road during the intended design life; the design of an overlay additionally requires an estimate of the traffic carried in the past by the existing pavement. Road Note 29[1] gives information which enables an estimate to be made of the expected cumulative traffic, but the data on which the figures are based are by now somewhat out of date, and the information is too restricted in some respects to meet current needs. Changes are required in relation to the distribution of commercial traffic between the lanes of multi-lane roads, in the range of possible annual growth rates of this traffic, and in the estimation of its saturation flows. Furthermore, the information is oriented towards new construction and is not presented in a form which enables past traffic to be estimated easily for the purposes of overlay design.

No great accuracy is possible in these predictions, of course; neither is it necessary: on current design standards for new pavements[1], the required total thickness of, eg, bituminous materials, is most sensitive to total traffic at high flows, but even doubling the total traffic from 20 to 40 million standard axles results in only about a ten per cent change in design thickness of roadbase and surfacing layers.

The present Report gives details of revised computations of cumulative traffic, and of the assumptions made in the computations. Two nomograms are described which embody the results obtained, one for estimating future traffic and one for estimating past traffic from a knowledge of present traffic and its past growth rate.

2. TRAFFIC-FLOW MODEL

The simple model of traffic flow adopted is fairly general, and by suitable choice of the parameters involved can be adapted to represent the relevant features of traffic flow on any type of road, from dual-carriageway three-lane motorways to single-carriageway two-lane roads.

It is assumed that, as the total (one-way) flow F of commercial vehicles increases, an increasing proportion of them move out from the nearside lane into the middle or off-side lane. Results of observations on dual-three-lane motorways[4] suggest that on these roads the proportion R of the total commercial traffic that continues in the nearside lane can be represented as indicated in Figure 1. Allowing for the existence of a saturation flow F_3 that cannot be exceeded, this relationship leads to the following equations giving the nearside lane flow F_s (in commercial vehicles/day) in terms of the total (one-way) flow F:–

$$\left.\begin{array}{lll} F_s & = F(1-af), & F \leqslant F_1 \\ F_s & = bF-cF^2, & F_1 < F \leqslant F_2 \\ F_2 & = dF, & F_2 < F \leqslant F_3 \\ F_s & = F_3, & F_3 < F \end{array}\right\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

with $F_1 < F_2 < F_3$ and where the parameters a, b, c, d, F_1, F_2 and F_3 have the significance indicated in Figure 1. Although the form of the curve of R in Figure 1 is based on observations made on dual-three-lane motorways, as noted above the model can be adapted for other types of road by appropriate choice of the parameters a, b, c, d, F_1, F_2 and F_3.

The total flow rate F in commercial vehicles per day is assumed to be given by

$$F = F_0 e^{rt} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

where F_0 is the initial flow, r is an exponential growth factor and t is the time (expressed in years in the following text).

Although the various flow rates and growth factors are treated as though they were instantaneous rates, they in fact represent trend lives for equivalent annual flow, with no separate account taken of diurnal or seasonal variations. The saturation flow F_3 is in consequence not the instantaneous saturation flow, and an appropriate value is difficult to establish with any precision; it will depend, among other things, on the extent to which vehicle operators would modify their journey schedules or their routes to avoid traffic peaks. The values adopted for the various parameters in the main series of calculations described below for dual-three-lane motorways, which as mentioned above were derived from observations of traffic flow on such roads, include plausible allowances for these and other effects.

3. ESTIMATION OF FUTURE TRAFFIC

With the above assumptions, the total cumulative traffic (commercial vehicles), T, carried by the nearside lane during a time t is:–

$$T = \int_0^t F_s(t)\,dt \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where F_s is given by Equation (1). In view of the exponential growth law for the total flow rate F given by Equation (2) this can be written:–

$$T = \int_o^t F_s(rt)\,dt$$

$$= \frac{t}{p} \int_o^p F_s(p)\,dp \qquad \ldots\ldots\ldots\ldots \quad (4)$$

where $p = rt$ (5)

The discontinuities in the form of the function $F_s(p)$, brought about by the discontinuities in the form of the function R, require that this integral be evaluated separately in four different regions of the argument p, depending on the relationship of the flow rate F at any time to the critical flow rates F_1, F_2 and F_3, that is, for the ranges $0 < F \leqslant F_1$, $F_1 < F \leqslant F_2$, $F_2 < F \leqslant F_3$ and $F_3 < F$. In terms of the integration parameter p, the corresponding ranges are:–

$$\left.\begin{array}{ll} (1) & 0 < p \leqslant p_1 \\ (2) & p_1 < p \leqslant p_2 \\ (3) & p_2 < p \leqslant p_3 \\ (4) & p_3 < p \end{array}\right\} \qquad \ldots\ldots\ldots \quad (6)$$

where

$$p_i = rt_i = \ln F_i/F_o \qquad (i = 1, 2, 3) \qquad \ldots\ldots\ldots \quad (7)$$

3.1 Range 1: $0 < p \leqslant p_1$

The case $p = 0$ (ie $r = 0$) is considered separately below. In the range $0 < p \leqslant p_1$, Equation (5) becomes:–

$$T = \frac{t}{p} \int_o^p (F - aF^2)\,dp$$

$$= \frac{t}{p} \int_o^p (F_o e^p - aF_o^2 e^{2p})\,dp$$

Writing

$$\phi(x, y) = e^x - e^y \qquad \ldots\ldots\ldots\ldots \quad (8)$$

the total cumulative near-side lane flow is:–

$$T = \frac{t}{p}\left[F_o\,\phi(p,o) - \frac{aF_o^2}{2}\,\phi(2p,o)\right] \qquad \ldots\ldots\ldots\ldots \quad (9a)$$

3.2 Range 2: $p_1 < p \leqslant p_2$

Assume $p_1 > 0$, ie, $F_o < F_1$. Then:–

$$T = \frac{t}{p} \int_{o}^{p_1} (F - aF^2)\,dp + \frac{t}{p} \int_{p_1}^{p} (bF - cF^2)\,dp$$

$$= \frac{t}{p} \left[F_o\,\phi\,(p_1, o) - \frac{aF_o^{\,2}}{2}\,\phi\,(2p_1, o) + bF_o\,\phi\,(p, p_1) - \frac{cF_o^{\,2}}{2}\,\phi\,(2p, 2p_1) \right] \quad \ldots\ldots \text{(9b)}$$

Since $\phi\,(0, 0) = 0$, cases in which the initial flow exceeds F_1, ie, in which $p_1 < 0$, can be included in this equation if the p_i are re-defined as:–

$$\begin{aligned} p_i &= \ln F_i/F_o \qquad & F_i \geqslant F_o \\ &= 0 & F_i < F_o \end{aligned} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(7a)}$$

3.3 Range 3: $p_2 < p \leqslant p_3$

Using (7a), the total flow is given in this case by:–

$$T = \frac{t}{p} \left[F_o\,\phi\,(p_1, o) - \frac{aF_o^{\,2}}{2}\,\phi\,(2p_1, o) + bF_o\,\phi\,(p_2, p_1) - \frac{cF_o^{\,2}}{2}\,\phi\,(2p_2, 2p_1) + dF_o\phi\,(p, p_2) \right] \quad \text{(9c)}$$

3.4 Range 4: $p_3 < p$

Here

$$T = \left[\frac{t}{p} \;(F_o\phi\,(p_1, o) - \frac{aF_o^{\,2}}{2}\,\phi\,(2p_i, o) + bF_o\,\phi\,(p_2, p_1) - \frac{cF_o^{\,2}}{2}\,\phi\,(2p_2, 2p_1) + dF_o\,\phi\,(p_3, p_2) + dF_3\,(p - p_3) \right] \quad \ldots\ldots \text{(9d)}$$

3.5 Zero growth : $r = 0$

The relationships valid for zero growth rate in each of the ranges $0 < F \leqslant F_1$, $F_1 < F \leqslant F_2$, $F_2 < F \leqslant F_3$ and $F_3 < F$ are given in Equations (9e) to (9h) respectively.

$$T = t\,(F_o - aF_o^{\,2}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(9e)}$$

$$T = (bF_o - cF_o^{\,2})\,t \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(9f)}$$

$$T = dF_o t \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(9g)}$$

$$T = F_3 t \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(9h)}$$

All these expressions (9a) – (9h) for the total cumulative flow of commercial vehicles T can be written in the general form

$$T = \beta\,(F_o, p)\,t \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

with appropriate definitions of the function β within each of the four ranges.

4. ESTIMATION OF PAST TRAFFIC

Equation (2) giving the traffic-flow rate after a given time t in terms of the initial flow F_o can be inverted to give the initial flow rate F_o at the start of the period from the flow rate F_c at the end of the period:–

$$F_o = F_c e^{-p} \qquad . . . . \qquad (11)$$

To estimate total past traffic, it is therefore necessary only to evaluate in this way the initial flow F_o from the current flow rate F_c and the estimated value of p. This initial flow rate can then be inserted into Equation (9) to obtain the total flow of commercial vehicles over the period concerned. If the growth rate or the parameters discussed below for converting numbers of commercial vehicles into numbers of equivalent standard axles are known to have changed in some way during the total period considered, the period can be sub-divided, the "initial" flow for one interval becoming the "current" flow for the preceding.

5. CALCULATIONS

Values of the function β defined by Equation (10) above were computed for a range of values of F_o from 10 to 10 000 commercial vehicles/day and a range of values of p from 0 to 2.40, with the values of the flow parameters a, b, c, d, F_1, F_2 and F_3 tabulated in Table 1; these were derived from traffic observations on a dual-three-lane motorway.

TABLE 1

Parameter values used

Parameter	Values		Units
	Motorway	Single carriageway	
F_o	10 – 10 000	10 – 10 000	commercial vehicles/day
F_1	6 000	–	commercial vehicles/day
F_2	11 000	–	commercial vehicles/day
F_3	25 000	5 000 – 20 000	commercial vehicles/day
p	0 – 240	0 – 180	(% per year) x time
t	0 – 40	0 – 40	years
a	5×10^{-5}	0	per vehicle/day
c	2.5×10^{-5}	0	per vehicle/day
d	0.55	–	–

Computations were also made, as indicated in Table 1, over the same range of values of F_o and p, but with flow parameters representing a road on which no transfer of vehicles out of the near-side lane occurred, (ie, for a = c = o), and for saturation flows of 5 000, 10 000, 15 000 and 20 000 vehicles/day. The results obtained, however, proved rather insensitive to this change, except at high initial flow rates (near or exceeding the assigned saturation flow F_3), or at high values of the parameter p (ie, high growth rates and/or long times). This is illustrated in Table 2, which gives, for various values of the initial flow F_o and the parameter p, values of the ratio Q between the values of β computed respectively for the case in which no vehicles transfer from the near-side lane (ie, a single-carriageway two-lane road), and for the case of a dual-three-lane motorway, with vehicle transfer from the near-side lane given by Equation (1) and the parameter values quoted in Table 1. The results given are those computed for an assumed saturation flow for the single carriageway (two-lane) road of 10 000 vehicles/day; results for the other values of saturation flow showed similar behaviour.

TABLE 2

Values of the ratio Q for various values of F_0 and p

p	F_0 (vehicles/day)					
	10	25	150	1 500	5 000	10 000
0.0	1.00	1.00	1.01	1.08	1.33	1.67
0.2	1.00	1.00	1.01	1.09	1.38	1.58
0.4	1.00	1.00	1.01	1.10	1.43	1.45
0.6	1.00	1.00	1.01	1.12	1.48	1.31
0.8	1.00	1.00	1.01	1.14	1.52	1.18
1.0	1.00	1.00	1.01	1.16	1.51	1.06
1.2	1.00	1.00	1.02	1.19	1.43	0.98
1.4	1.00	1.00	1.02	1.23	1.34	0.94
1.6	1.00	1.00	1.02	1.28	1.22	0.90
1.8	1.00	1.00	1.03	1.33	1.13	0.88

6. RESULTS

The most practically useful and compact form of presentation of the results is by an appropriate nomogram, representing the total cumulative traffic T as a function of the variables F_0, r and t. Such a nomographic representation, however, requires that T be expressible in terms of several functions each dependent on one of the variables only, so that separate scales of each can be drawn, that is, that T be expressible in the form

$$T = G_1(F_0)\, G_2(r)\, G_3(t)$$

Equation (10) above, that is,

$$T = \beta(F_0, p)\, t$$

shows that, if the set of variables F_0, r and t is replaced by the set F_0, p and t, then the explicit dependence of T on the time t is of the required form, but that the two variables F_0 and p are joint arguments of the function β, and their effects cannot be separated analytically. Exact nomographic representation of the results is therefore not possible.

However, Figure 2 shows the variation with F_0 and p of the function S_0, defined as

$$S_0 = \beta(F_0, p) / \beta(500, p)$$

As can be seen, the effect of p on this function is small, except at large values of F_0 and of p (ie, large values of r and/or t). To the accuracy indicated in this figure, therefore, T can be written

$$T = S_1 (F_0) S_2 (p) t \qquad (12)$$

where S_1 is defined as an average of the values of S_0 at each value of F_0, and $S_2(p)$ is defined as

$$S_2 (p) = \beta (500, p)$$

Equation (12) is now of the form required for a nomographic representation.

The computer program was therefore arranged to draw a nomogram from the results, based on an optimum choice of the values of the function S_1. This nomogram is shown in Figure 3. With the values of S_1 chosen, it represents the results of the calculations with an accuracy of ± 10 per cent for all the values of p covered if $F_0 < 1\,000$ commercial vehicles per day. For values of $F_0 > 1\,000$, it is accurate to within ± 10 per cent for all values of $p < 1.5$. For $F_0 > 1\,000$ and $p > 1.5$, the discrepancy between the nomogram and the calculated results increases, until at $F_0 = 10\,000$ vehicles/day and p = 2.40 the nomogram result is about 65 per cent of the calculated result. In view of the uncertainties that are inevitably associated with the prediction of traffic over the long times and at the high growth rates implied by values of p of this order (6 per cent per annum growth rate maintained for 40 years), and the relatively low sensitivity of pavement thickness to the design traffic, discrepancies of this magnitude in this region of the parameters F_0 and p are not practically significant.

The results of similar computations, using values of the parameters a, b, c, d, F_1, F_2 and F_3 representing other types of roads, could be treated similarly, and nomograms produced appropriate for each class. As Table 2 shows, however, the results for the two extreme cases of a single-carriageway two-lane road (with no vehicle transfer from the near-side lane and a relatively low saturation flow), and a dual-three lane motorway, differ significantly only if the total flow is, or becomes, comparable with the value of F_1 (6 000 vehicles per day) for the motorway, or approaches saturation flow for the single-carriageway two-lane road. Roads carrying or expected to carry such high flows however, would more commonly be designed to have a higher capacity, with a saturation flow and vehicle-transfer characteristics intermediate between those for a single carriageway two-lane road and those for a motorway. The computed total near-side lane flow on such a road would then be intermediate between the results for these two extreme cases, as would also be the nomogram discrepancies. For these reasons, it is unnecessary to provide separate nomograms for the various classes of roads; the nomogram in Figure 3 can be used for all types, though with the proviso that if, exceptionally, the road is expected to become saturated early in its life, the total flow should be derived by assuming a growth rate of zero. Similarly, if for geometrical or other reasons the vehicle-transfer characteristics are abnormal, some allowance should be made for differences between the actual transfer characteristics and those on which the nomogram is based (see Figure 1 and Table 1). As Table 2 shows, however, the discrepancy between the calculated value and that deduced from the nomogram is unlikely to exceed a factor of two, even if no such allowances are made, and as noted earlier the consequential effects of differences of this order on the design are relatively small.

A similar nomogram was also produced for the estimation of past traffic from estimates of the current daily flow, the parameter p and the period of time considered, t. This nomogram is shown in Figure 4. It includes an additional nomogram intended for the estimation of the initial flow at the start of the period from estimates of the current flow and of the parameter p; this is provided to facilitate sub-division of the period of interest in cases in which either the growth rate r or the parameters governing the conversion of the number of commercial vehicles to number of equivalent standard axles is known to have changed. This nomogram represents the calculated results with an accuracy similar to that of Figure 3.

The method of use of the nomograms is indicated diagrammatically on them, and is also described in the Appendix.

The nomogram calculations were based on the three parameters t, F_0 and $p = rt$, where r is the exponential growth factor in Equation (3). In practice, it is normal to work not in terms of the growth factor r, but of the growth rate r' expressed as per cent increase per annum. The relation between r and r' is, strictly speaking,

$$r' = 100\,(e^r - 1)$$

and is therefore non-linear. Over the range of growth rates covered by the calculations, however (ie, 0 to 6 per cent per annum) the ratio r'/r is constant to within ± 1% at an average value of 101.5. The p axes on the nomograms have been scaled in terms of $p' = r't$, in place of $p = rt$, using this average conversion factor. It may be noted that at the very high growth rate of 30 per cent per annum, the ratio r'/r reaches 116.6, and the nomogram will underestimate the total flow by about 8%.

7. CONVERSION TO STANDARD AXLES

In principle, the nomograms allow the total traffic carried by a road to be estimated in terms of the numbers of commercial vehicles. For design purposes, this information has to be converted to relate to the damage done by the traffic. This depends, among other things, on the number of axles per commercial vehicle, and on the damage done by each axle. As an approximation, it is conventionally assumed that the damage done by a given axle load is roughly proportional to the fourth power of the load, and with this assumption the damaging power of a given mix of axle loads can be expressed in terms of the number of standard 80 kN axles that are equivalent in terms of damaging power to the actual axles.

To the extent that these two factors, the number of axles per commercial vehicle, and the relative damaging power of the actual mix of axle loads, have been constant (or are expected to remain constant) over the period considered, the nomograms can be interpreted directly in terms of the numbers of equivalent standard axles. That is, if the "initial flow" F_0 is set equal to the initial flow measured in standard axles, and the growth factor is set equal to the growth rate of standard axles, the results will also be expressed in standard axles.

However, measurements (carried out mainly on heavily trafficked roads) indicate that there have been increases in both factors in recent years, and there is no evidence to suggest that these trends have halted. In any case, there are, not surprisingly, appreciable differences as regards these two factors between different classes of roads. For all these reasons, the nomograms leave issues relating to the relative damaging power of the traffic for separate consideration.

8. CONCLUSIONS

Computations related to the estimation of future and past traffic have been made, which bring up to date and extend the range of information contained in Road Note 29. It has been found possible to represent the results of the computations for a dual-three-lane motorway by a simple nomogram, which represents the results with an accuracy which is generally better than ± 10 per cent, worsening to give about a 35 per cent underestimate at the extreme conditions representing the largest growth factor $p = rt$ combined with the highest initial flow F_0. The same nomogram has also been found to represent with similar accuracy the results of calculations with flow parameters chosen to represent the extreme case of a single-carriageway two-lane road, provided that it is not applied in situations where the low saturation flow associated with such roads is likely to be reached within the period considered.

The results have also been used to prepare a second nomogram to carry out the traffic calculations necessary for overlay design. It is of comparable accuracy to the first.

It is intended that these nomograms will be included in a pending revision of the design inputs related to traffic required for Road Note 29 and for overlay design.

9. ACKNOWLEDGEMENTS

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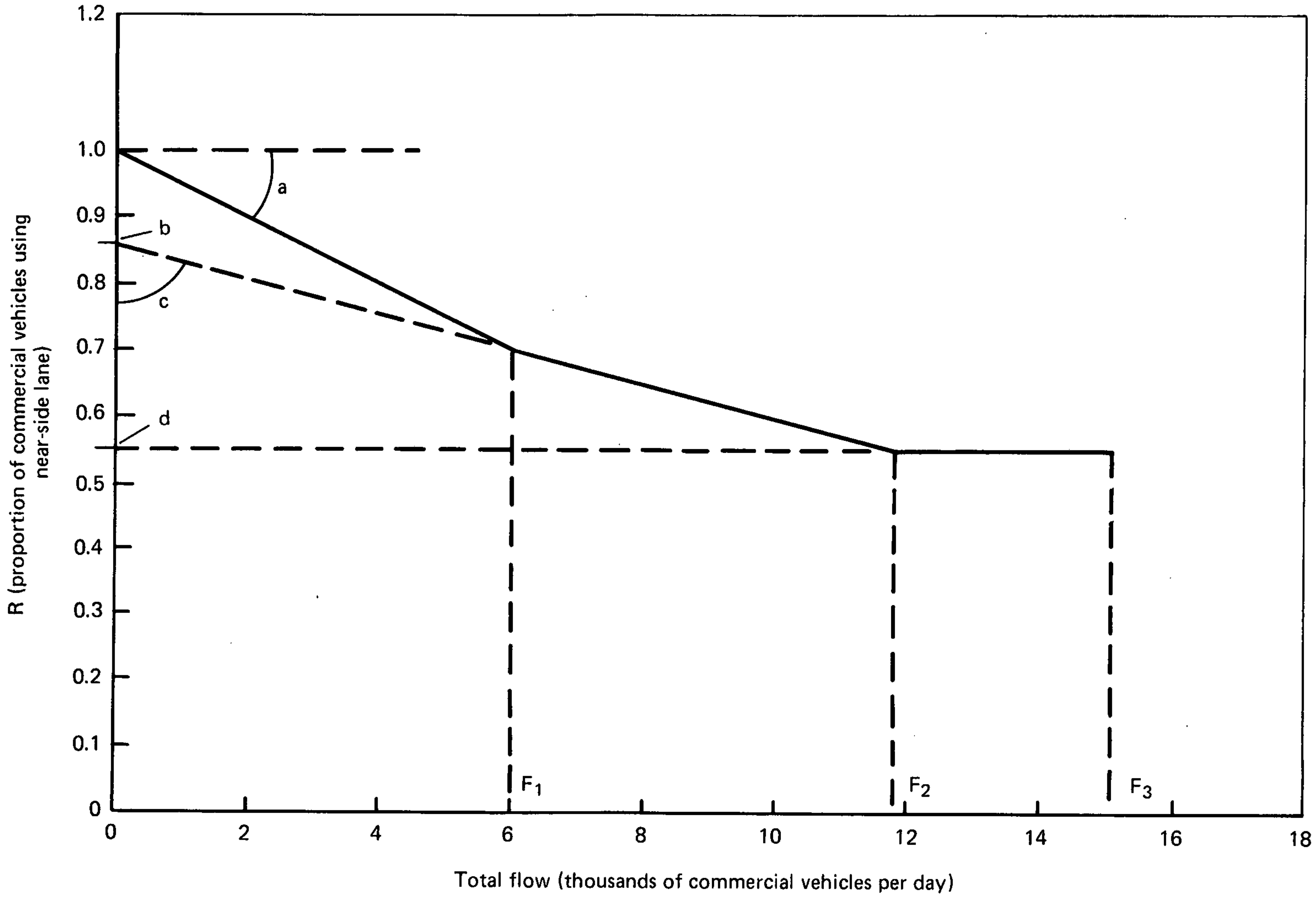

Fig. 1 ASSUMED TRAFFIC-FLOW CURVE

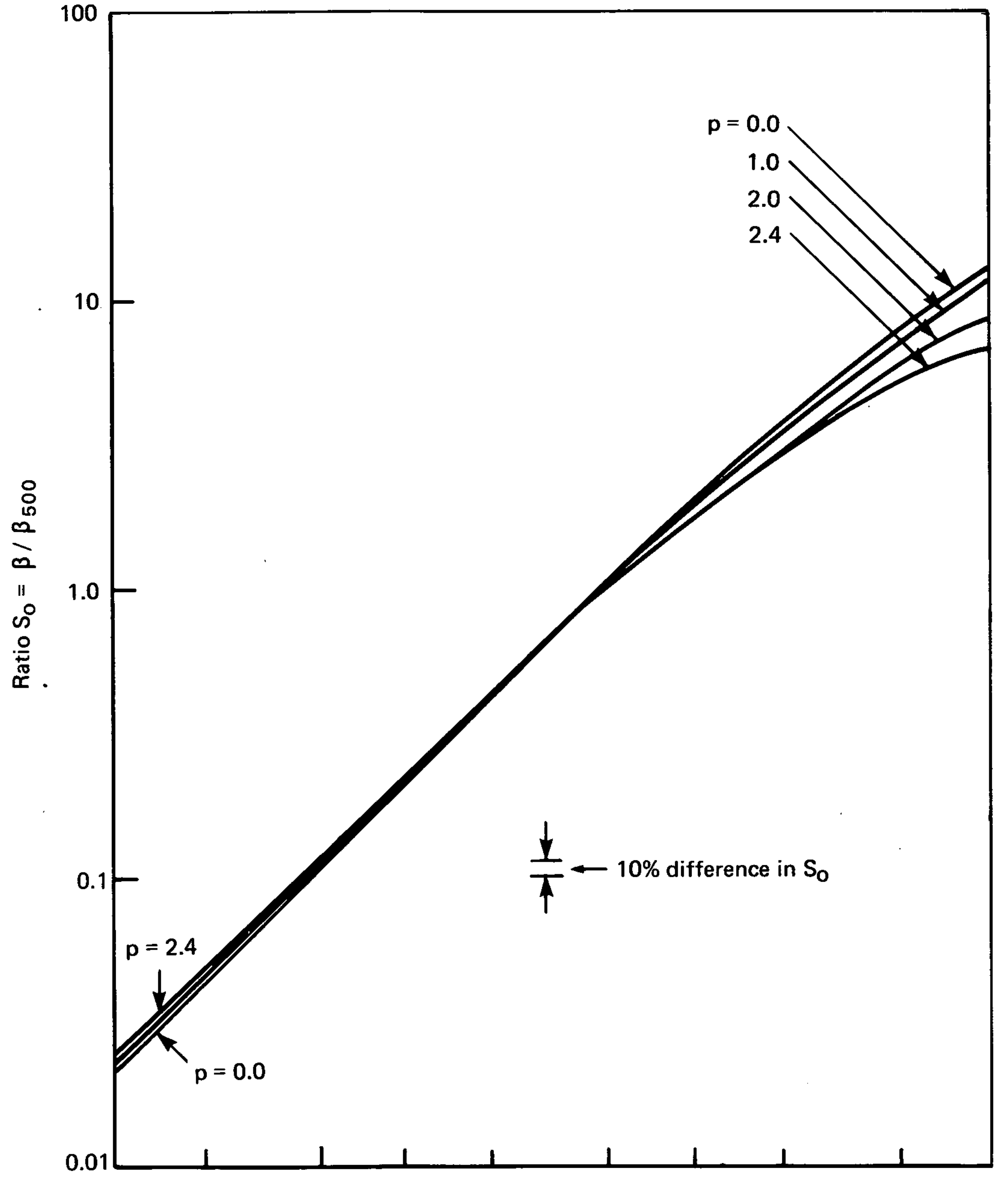

Fig. 2 VARIATION OF S_o WITH F_o AND p

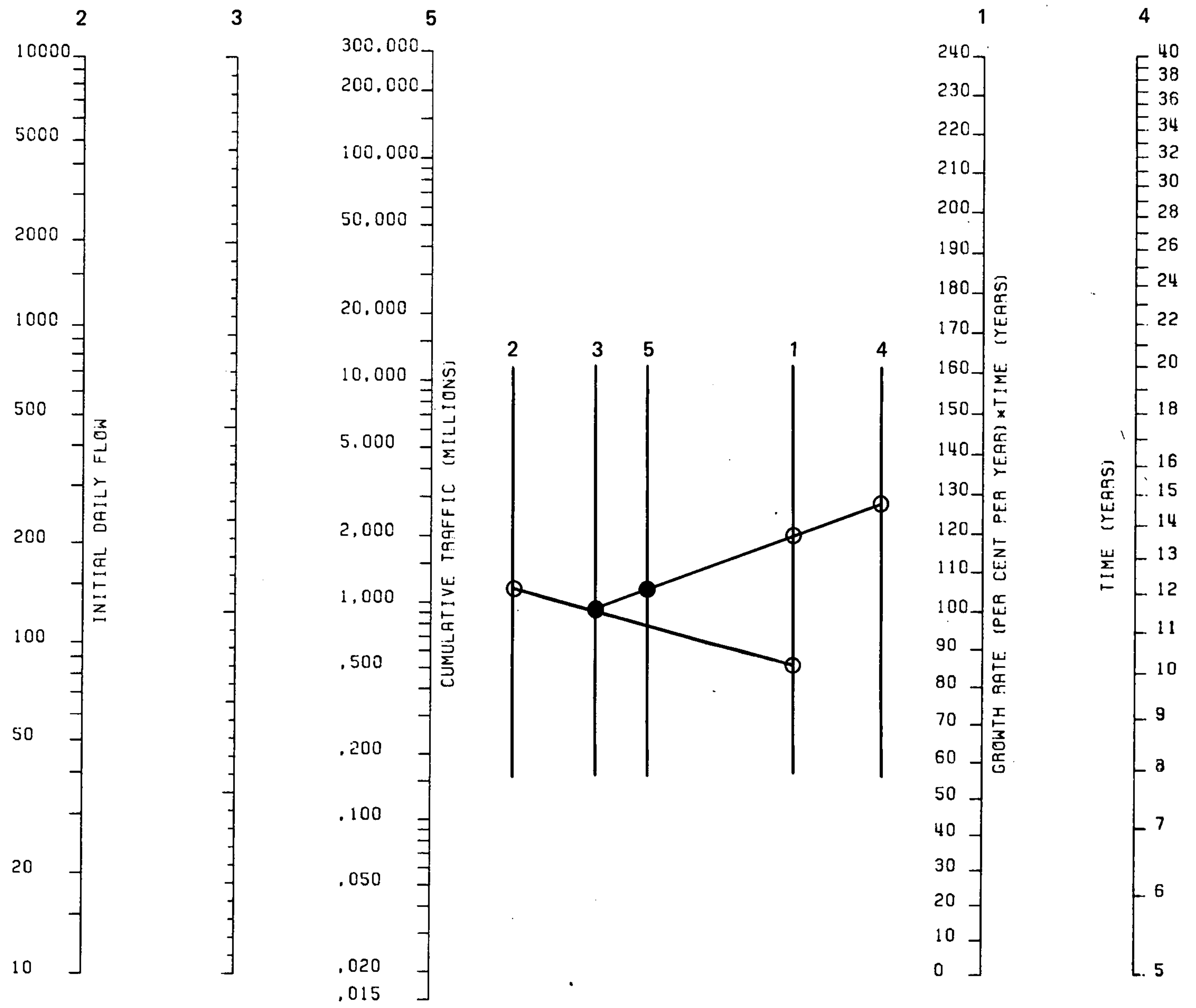

Fig. 3 NOMOGRAM FOR FORWARD ESTIMATION OF CUMULATIVE ONE-WAY TRAFFIC IN THE LEFT HAND LANE (COMMERCIAL VEHICLES)

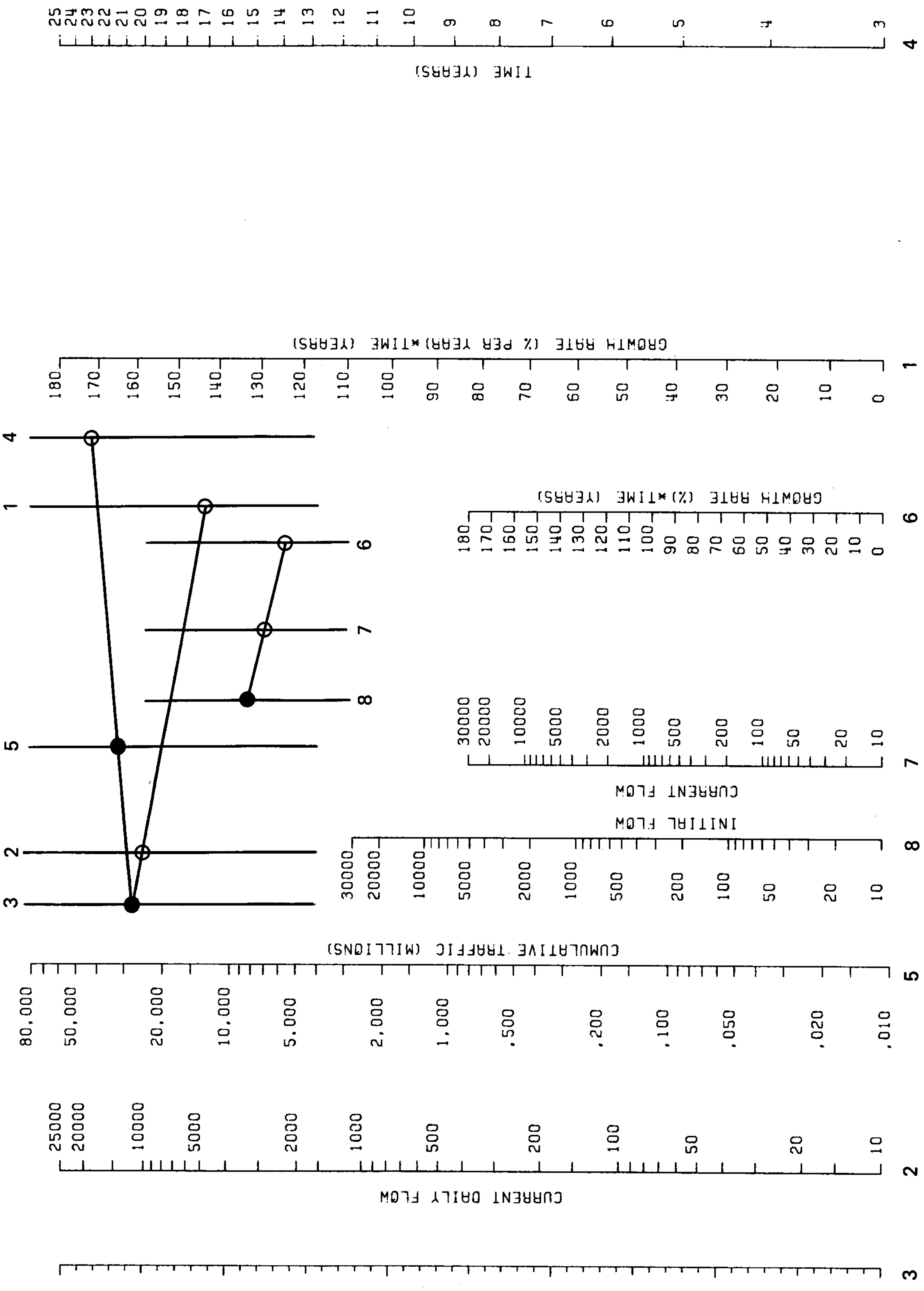

Fig. 4 NOMOGRAMS FOR BACKWARD ESTIMATION OF CUMULATIVE ONE-WAY TRAFFIC IN THE LEFT HAND LANE (COMMERCIAL VEHICLES)

11. APPENDIX

METHOD OF USE OF THE NOMOGRAMS

The method of use is indicated diagrammatically on each nomogram. The open circles on the scales in the diagrams represent data (input) values, and the solid circles represent intermediate or final result (output) values. The various scales on the diagrams and in the nomograms are numbered conformably.

11.1 Figure 3 Nomogram – forward estimation

(i) Identify the point on Scale 1 corresponding to the appropriate growth rate and design life.

(ii) Join this point with a straight line to the point in Scale 2 corresponding to the total (one-direction) daily flow of commercial vehicles.

(iii) Determine the intersection of this line with Scale 3.

(iv) Join this intersection point to the point on Scale 4 corresponding to the design life.

(v) Read off the total cumulative (one-direction) flow of commercial vehicles at the intersection of this line with Scale 5.

11.2 Figure 4 Nomogram – backward estimation

(i) Join with a straight line the point on Scale 1 corresponding to the estimated growth rate and period of time concerned to the point on Scale 2 corresponding to the current daily (one-direction) flow of commercial vehicles.

(ii) Identify the intersection of this line with Scale 3.

(iii) Join this point with a straight line to the point on Scale 4 corresponding to the time period.

(iv) Read off the total cumulative flow over the period at the intersection of this line with Scale 5.

If the total period is being sub-divided into say two periods because of changes in either or both the growth rate or the conversion factors between commercial vehicles and standard axles, it is necessary to be able to estimate the flow at the start of the second period; the nomogram can then be re-entered to determine the total flow over the first period by taking this value as the new current daily flow. The subsidiary nomogram, Scales 6–8, is provided for this purpose. To use it:–

(i) Identify in Scale 6 the point corresponding to the growth rate and time, and join it to the point in Scale 7 corresponding to the current daily flow.

(ii) The initial flow is given by the intersection of this line (extended) with Scale 8.

The main nomogram can then be re-entered for the earlier period with the "current flow" on Scale 2 set to this value. The process can be repeated to cover as many intervals as necessary, summing the contributions from each interval, after making any necessary adjustments for changes in the nature of the traffic.

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