is the preferred model for estimating cost in the optimization procedure for fixed-time traffic signalized intersections for undersaturated and saturated conditions.

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Peaking Characteristics of Rural Road Traffic

PIETER W. JORDAAN AND CHRISTO J. BESTER

A methodology for estimating the traffic volume on rural roads for any of the highest thousand hours of the year is presented. The methodology requires estimates of the annual average daily traffic and a peaking characteristic. Also presented is the derivation of the latter from the data obtained from permanent traffic counters. It is found that the peaking characteristic is related to the fraction obtained by dividing the thirtieth highest hourly volume by the annual average daily traffic as well as by the average length of through trips on the road link to which it is applicable. It is hoped that this methodology will create a sound base for further research into traffic volume variations and design hour volume.

Peaking of rural traffic is a well-known phenomenon. How to take such peaking into account is less well established. Two approaches are in use in highway engineering practice, namely, the design hour approach and the flow regime approach.

The design hour approach was established in the United States by Peabody and Norman in 1941 *(1)*. They found that if the hourly traffic counts from a year's records were sorted from high to low and plotted against rank number, there was a "knee" at about the thirtieth highest hour. Since 1941 this concept of using some hourly volume to represent the peaking characteristic of the traffic on a road has received much support. It is embodied in many design textbooks *(2–4)*, usually of U.S origin.

In South Africa this concept is also well-known and applied by most road authorities *(5)*. Some local research has been done into the relationship between K [the fraction obtained by dividing the thirtieth highest hourly volume by the annual average daily traffic (AADT)] and the AADT *(6)*. To date, no real causal parameter for estimating K has been found. K is generally believed to vary as follows:

- Roads with a high proportion of recreational traffic: $K > 0.25$,
- Average roads: $0.15 < K \leq 0.25$, and
- Roads with little peaking: $K \leq 0.15$.

It has been observed that as AADT increases, there is a tendency for K to decline *(6)*.

The flow regime approach was established by Dawson in the United Kingdom in the late 1960s *(7)*. In this approach, the 8,760 hr of the year are divided into groups with constant flow characteristics. Dawson's original flow regimes for rural roads are given in Table 1. Over the years, this approach has been refined by the Transport and Road Research Laboratory in the United Kingdom *(8)*. It is also used in the COBA procedures for project evaluation *(9)*.

In South Africa, this approach is also used in the RODES2 program developed by Bester *(10)*, in which the flow regimes are differentiated by K, the fraction of the thirtieth highest hourly volume.

From the foregoing it is clear that a knowledge of hourly vehicular flow is important to the roads engineer. Not only is a knowledge of the flow during the thirtieth highest hour required, but the use of sophisticated project evaluation pro-

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TABLE 1 FLOW REGIMES FOR RURAL ROADS ACCORDING TO DAWSON

Flow Group	No. of Hours Represented (1)	Avg Flow in Veh/Hr as a Fraction of AADT (2)
1	3,800	0.010
2	3,420	0.054
3	1,160	0.083
4	380	0.115

Note: (1) × (2) summed over the four groups = 365 = number of days in the year.

cedures requires estimates of the vehicular flow in other ranked hours of the year.

Therefore, the purpose of this paper is to develop a methodology for the determination of hourly volumes on rural roads that is able to replace the current methodologies and that will create a sound base for further research into traffic volume variations.

RELATIONSHIP BETWEEN HOURLY VOLUME AND RANK NUMBER, N

Analysis and Development of Theory

If hourly counts at continuous counting stations are sorted from high to low and plotted versus rank number on a log–log scale, the plot between the tenth highest hour and the 1,000th highest hour forms a virtual straight line. This implies that for this region, the following relationship holds:

$$F = aN^b$$

where

F = hourly count/AADT,
a and b = calibration values, and
N = rank number.

Lines were fitted by means of least-squares techniques to determine a and b for the data from each of 65 different counting stations. Figure 1 shows an example of the hourly counts plotted at a continuous station that was counted for 18 hr/day. During this phase, almost all of the regressions resulted in correlation coefficients (R) exceeding 0.95, indicating the validity of the relationship $F = aN^b$.

While the values of a and b were being studied, it transpired that there was a definite monotonic relationship between the values of a and b. If lognatural (ln) a is now plotted against b, a set of points is obtained between which a straight line is the obvious relationship, as shown in Figure 2. The correlation coefficient (R) for the straight line fit between ln a and b in Figure 2 is 0.989. The 95 percent confidence limits are also shown in Figure 2.

In considering Figure 2, it is obvious that a straight-line relationship between A (= ln a) and B (= b) exists, that is,

$$A = c + mB \quad (1)$$

$$\text{or } \ln a = c + mb \quad (2)$$

It can therefore be stated that a family of linear equations exists:

$$[F_n(x)]_{n \varepsilon \mathcal{N} = (1,2 \ldots ,65)} = y = A_n + B_n x$$

such that $A_n = c + mB_n$ for every $n \varepsilon \mathcal{N}$

From this it follows that a point $P \varepsilon X \times Y$ exists, which is a solution to the family of linear equations ($y = A_n + B_n x$).

PROOF

For simplicity, consider $\mathcal{N} = (1, 2)$:

The family of linear equations are therefore

$y = A_1 + B_1 x$ and $y = A_2 + B_2 x$

from which it follows that

$$x = -[(A_1 - A_2)/(B_1 - B_2)]$$

By using

$$A_n = c + mB_n \qquad \text{for } n = 1, 2$$

it is found that

$$x = -\{[c + mB_1 - (c - mB_2)]/(B_1 - B_2)\}$$
$$= -[m (B_1 - B_2)/(B_1 - B_2)]$$
$$= -m$$

By substituting this result in $y = A_1 + B_1 x$, it follows that

$$y = A_1 - B_1 m$$

but

$$A_1 = c + mB_1$$

therefore,

$$y = c + mB_1 - mB_1$$
$$= c$$

Therefore

$P \varepsilon X \times Y$ and $P = (-m, c)$

The coordinates $(-m, c)$ of P are in logarithmic space. If the coordinates in normal space are denoted as (N_o, F_o) it follows that

$$c = \ln F_o$$

and

$-m = \ln N_o$

It then follows that

$$F_o = e^c \tag{3}$$

and

$$N_o = e^{-m} \tag{4}$$

Substituting Equations 3 and 4 in Equation 2 and rearranging:

$\ln F_o = \ln a + b \ln N_o$

Therefore

$F_o = aN_o^b$

This point at the N_o highest hour, where the hourly traffic volume is a fraction F_o of the AADT, is therefore common to all the counting stations, and is called the focal point.

For the 65 records analyzed, F_o and N_o were determined by applying the relationships in Equations 3 and 4 to the equation of the straight line in Figure 2, resulting in $F_o = 0.072$ and $N_o = 1{,}030$. These values N_o and F_o are the same for all counting stations, and the straight line on the log–log graph of the fraction of AADT versus rank number should pass through this focal point for all counting stations. Using $F = aN^b$ and the relationship $F_o = aN_o^b$, it is easily demonstrated that $F_o = N^b/N_o^b$.

If β is now introduced in the place of b to distinguish between b (calibrated in the initial analysis) and the new value of b (to be calibrated such that $N_o = 1{,}030$ and $F_o = 0.072$), it is found that

$$F/F_o = (N/N_o)^\beta \tag{5}$$

There is therefore only one parameter, β, that determines the peaking characteristics of a given road. (However, the coordinates of the focal point F_o and N_o must be calibrated for a given geographical area.)

If Equation 5 is applied to the data sets, β can be estimated. Figure 3 shows a typical result on normalized scales.

Final Formulation of Peaking Curve

From Equation 5,

$F/F_o = (N/N_o)^\beta$

$F = F_o (N/N_o)^\beta$

where F is U_n/AADT, and U_n is hourly volume in the nth highest hour (found to be 0.072 and 1,030, respectively, for South African roads).

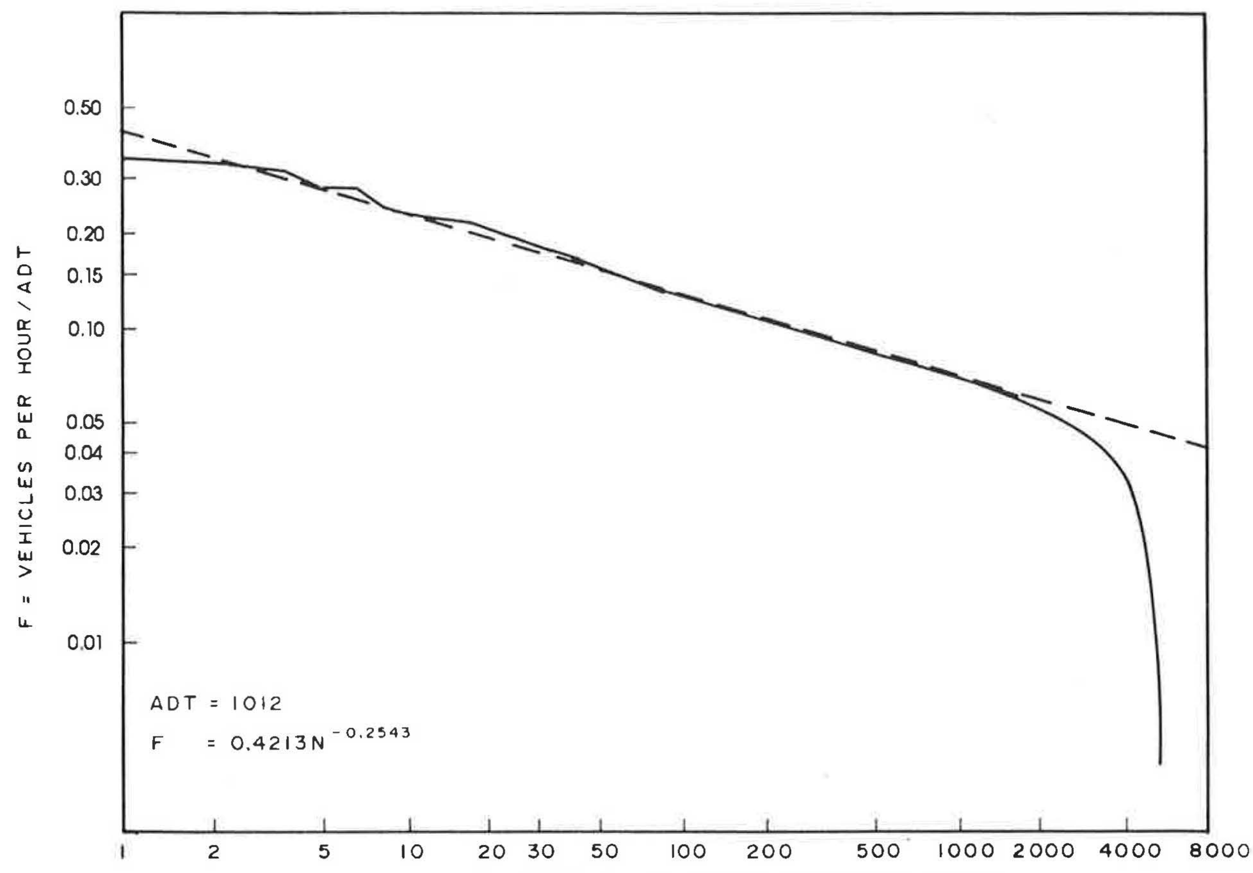

FIGURE 1 Hourly counts and straight-line fit at counting station CH/A, between Christiana and Warrenton, on P3-1.

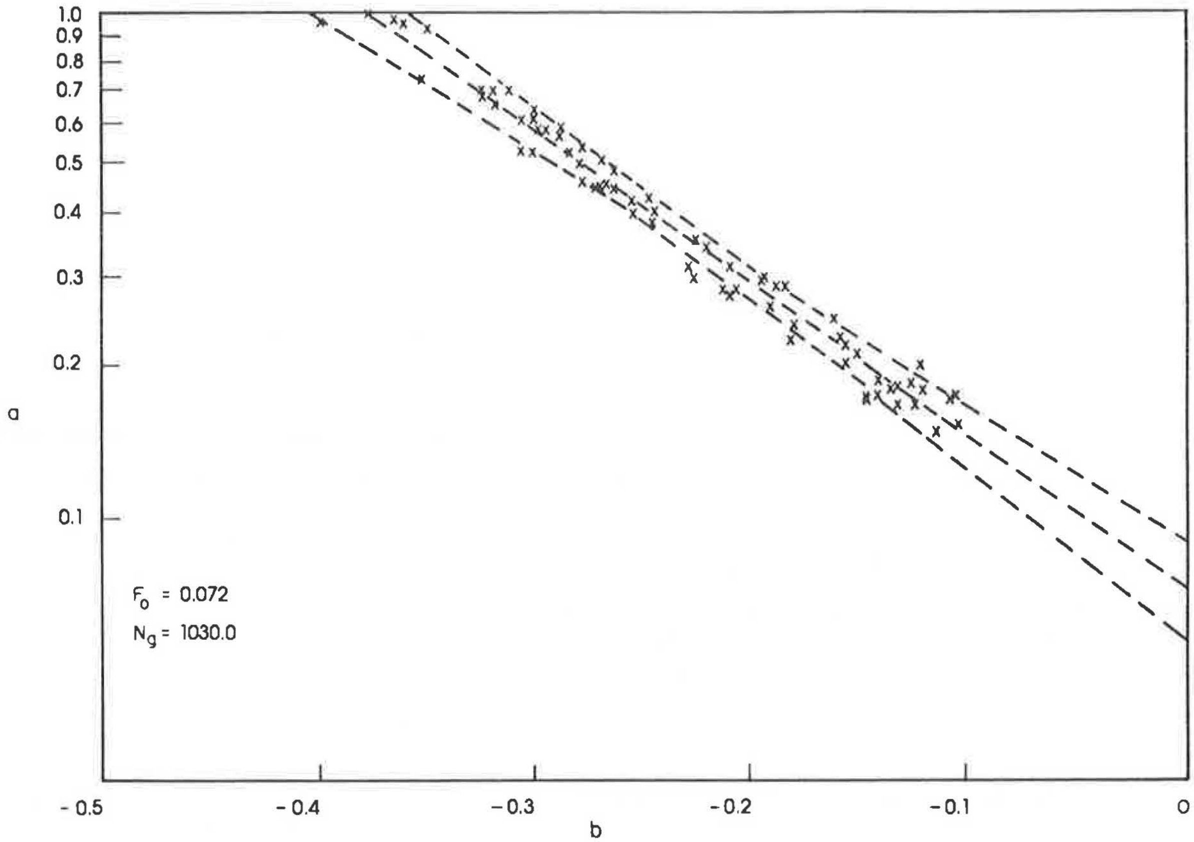

FIGURE 2 Relationship between values of a and b shown on log natural scales.

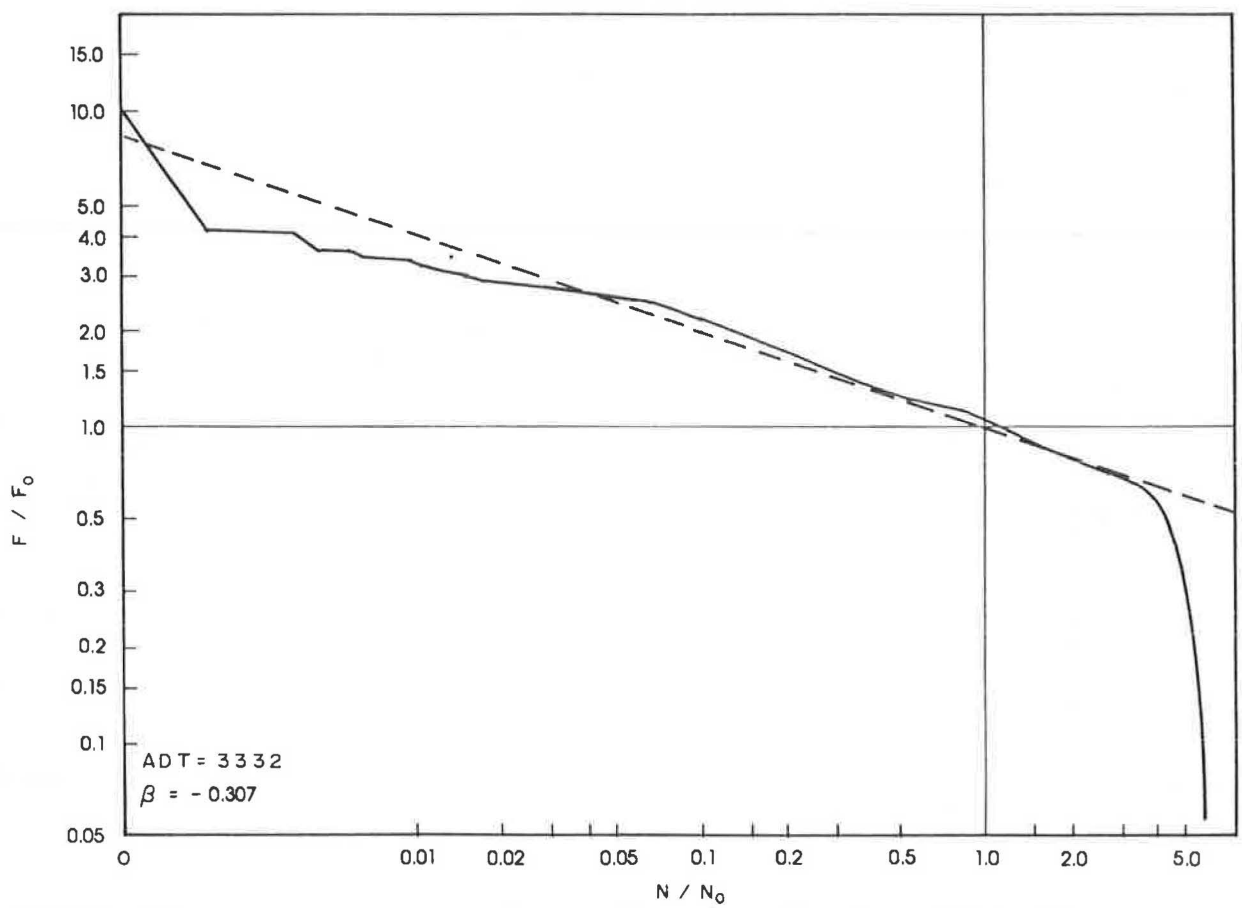

FIGURE 3 Normalized traffic counts at station KG/A, between Krugersdorp and Rustenburg on P16-1, for 1975.

Therefore

$U_n/AADT = F_o\ (N/N_o)^\beta$

$$U_n = F_o \cdot AADT \cdot (N/N_o)^\beta \quad (6)$$

with

$F_o = 0.072$ and $N_o = 1{,}030$

$$U_n = 0.072 \cdot AADT \cdot (N/1{,}030)^\beta \quad (7)$$

Figures 4 and 5 are graphic illustrations of the model fit. The former shows the fit at a specific location for the 1,000 highest hours and the latter at all stations for the thirtieth highest hour.

SOME PROPERTIES OF PEAKING CURVE

The following relationships can easily be derived:

Number of vehicles in the m highest hours (S_m):

$$S_m = \{(F_o \cdot AADT)/[(\beta + 1) \cdot N_o^\beta]\}\ m^{\beta+1} \quad (8)$$

where $m < N_o$. If the calibrated values $F_o = 0.072$ and $N_o = 1{,}030$ are used, this equation reduces to

$$S_m = \{(0.072 * AADT)/[(\beta + 1)\ 1{,}030^\beta]\}\ m^{\beta+1} \quad (9)$$

where $m < 1{,}030$.

The fraction of traffic in the m highest hours (F_m):

$$F_m = S_m/(365 * AADT) \quad (10)$$

Number of hours in which the volume exceeds U (N_u):

$$N_u = N_o\ [U_n/(F_o \cdot AADT)]^{1/\beta} \quad (11)$$

where $N_u < N_o$.

Again, if $F_o = 0.072$ and $N_o = 1{,}030$ are used,

$$N_u = 1{,}030\ [U_n/(0.072\ AADT)]^{1/\beta} \quad (12)$$

where $N_u < 1{,}030$.

DETERMINATION OF PEAKING CHARACTERISTICS, β

From Continuous Traffic Counts

The hourly counts are ranked, and a normalizing procedure is carried out, that is,

y = hourly count/($AADT \cdot F_o$)

where $F_o = 0.072$; and

X = rank number/N_o

where $N_o = 1{,}030$.

Now $y = X^\beta$ or $\ln y = \beta \ln X$ and a least-squares calibration can be performed to determine β.

BY STUDYING VALUES OF β AT KNOWN LOCATIONS

The frequency and magnitude of the volume of seasonal traffic are the most important determinants of β. If the frequency is high and the magnitude of the traffic volume low, β will tend toward a value of –0.10. On the other hand, if the frequency is low and the magnitude of the traffic volume is high, β will tend toward a value of –0.40.

In selecting a value for β, the following can be used as a guide:

- $\beta = -0.10$ indicates a road that has virtually no peaking,
- $\beta = -0.20$ is typical of a road that has average peaking, and
- $\beta = -0.40$ is typical of a road that has high seasonal peaks.

By Estimating a Value for K, the Fraction of the Thirtieth Highest Hourly Volume

Because engineers may have a historical feel for the K value and may therefore find it easier to estimate this parameter, the following relationship can be used to determine β:

$$\beta = (\ln K - \ln F_o)/\ln (30/N_o) \quad (13)$$

if $F_o = 0.072$ and $N_o = 1{,}030$, this reduces to

$$\beta = -0.283 \ln K - 0.744 \quad (14)$$

This relationship is demonstrated in the following table.

K (fraction)	β
0.10	–0.092
0.15	–0.207
0.20	–0.289
0.25	–0.352
0.30	–0.403

Because of the mathematical relationship between K and β, the β-methodology would result in exactly the same thirtieth highest hour volume estimate as would the K-methodology. However, the β-methodology allows the estimate of flows in the other ranked hours of the year as well.

From the Relationship Between β and Average Length of Through Trips on a Road

By using the origin–destination matrix together with the assignment routine of the South African Rural Traffic Model, it was possible to determine the average length of through trips on each of the 1,320 links in the model network *(11)*. For those links for which continuous traffic counting data were available,

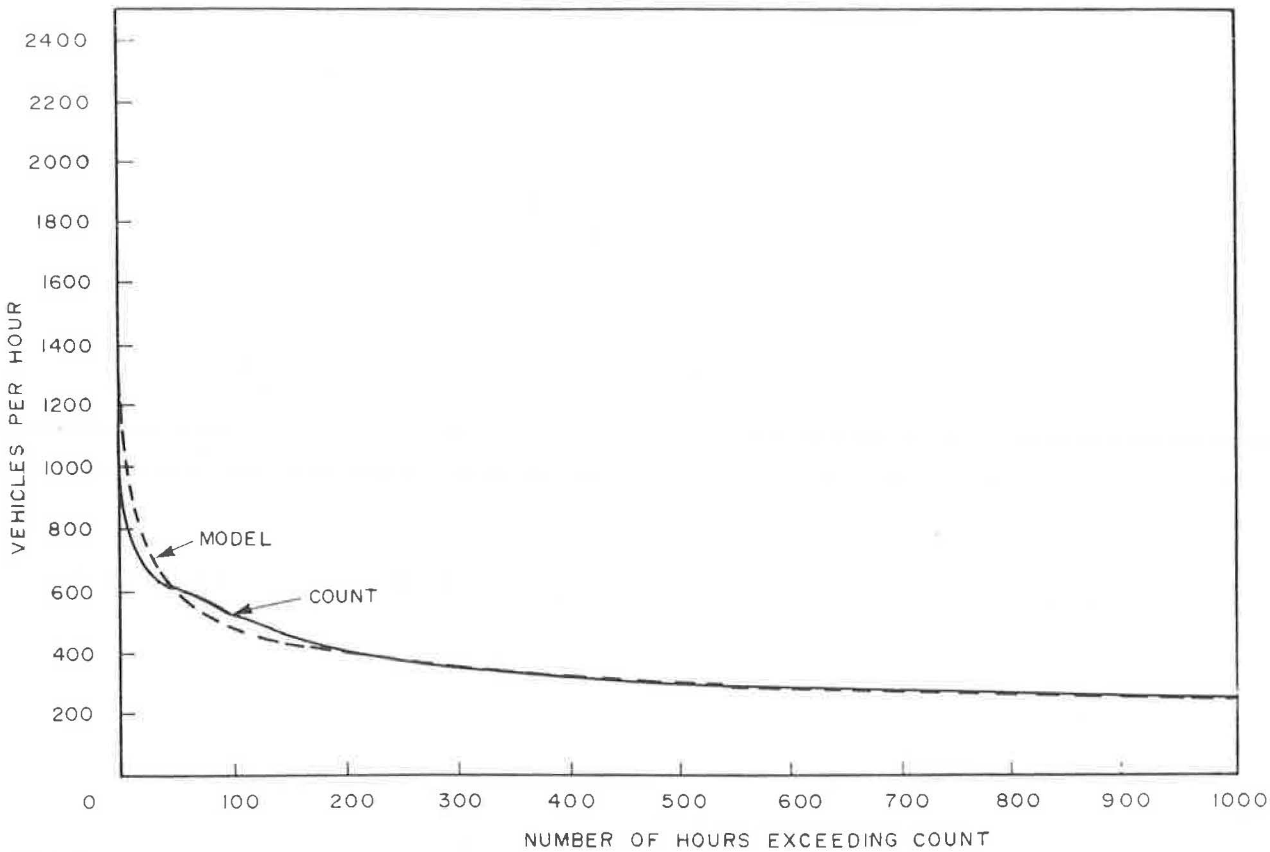

FIGURE 4 Actual counts and modeled traffic at station KG/A, between Krugersdorp and Rustenburg on P16-1.

β was plotted against the average length of through trips. The plot is shown in Figure 6.

The correlation coefficient R for the linear relation shown in Figure 6 is 0.862. The fitted line is given by

$$\beta = 0.0358 - 0.00076L \tag{15}$$

where L is average length of through-trips on the link (km).

Therefore, if the average trip length on a road is known, say from origin–destination surveys or modeling procedures, the peaking characteristic can be estimated. Table 2 gives some trip lengths and associated β-values.

APPLICATIONS OF β-METHODOLOGY

The fact that the hourly flow in any of the 1,000 highest hours can be estimated leads to many new applications. If the flow in the remainder of the hours of the year is assumed to be linearly related to the rank number—which, based on limited samples, is true for the South African situation—the hourly flow in all of the hours of the year can be estimated. In the geometric design process, the following procedures could then be followed.

Phase 1:

- Estimate the base year AADT and β for the road in question.
- Estimate the design year AADT by using growth rates or modeling procedures.
- Estimate the design year β by considering the change in character and/or function of the road.
- Use the β-methodology to determine the hourly flows. This leads to graphs indicating the number of hours in any given year in which the traffic exceeds specified levels of service (LOS). The percentage of traffic that experiences a given LOS and how this changes with time can also be determined. This leads to new insights into the service provided by the proposed facility.

Phase 2:

- Determine the relationship between vehicular operating costs (VOC) and hourly volumes for the specific design alternative.
- Multiply the hourly flow by the VOC for that specific flow, sum over the 8,760 hr of the year, discount to the present for every year of the design life of the facility, resulting in the total discounted VOC on the facility.
- By repeating these two steps for various design alternatives, the differential VOC can be estimated. By comparing this with the differential construction cost, the most economical design can be found.

These procedures, seemingly tedious, are easily performed on modern high-speed computers.

FUTURE RESEARCH

The transferability of the model to the whole of the Republic of South Africa is currently being investigated. Transferability to

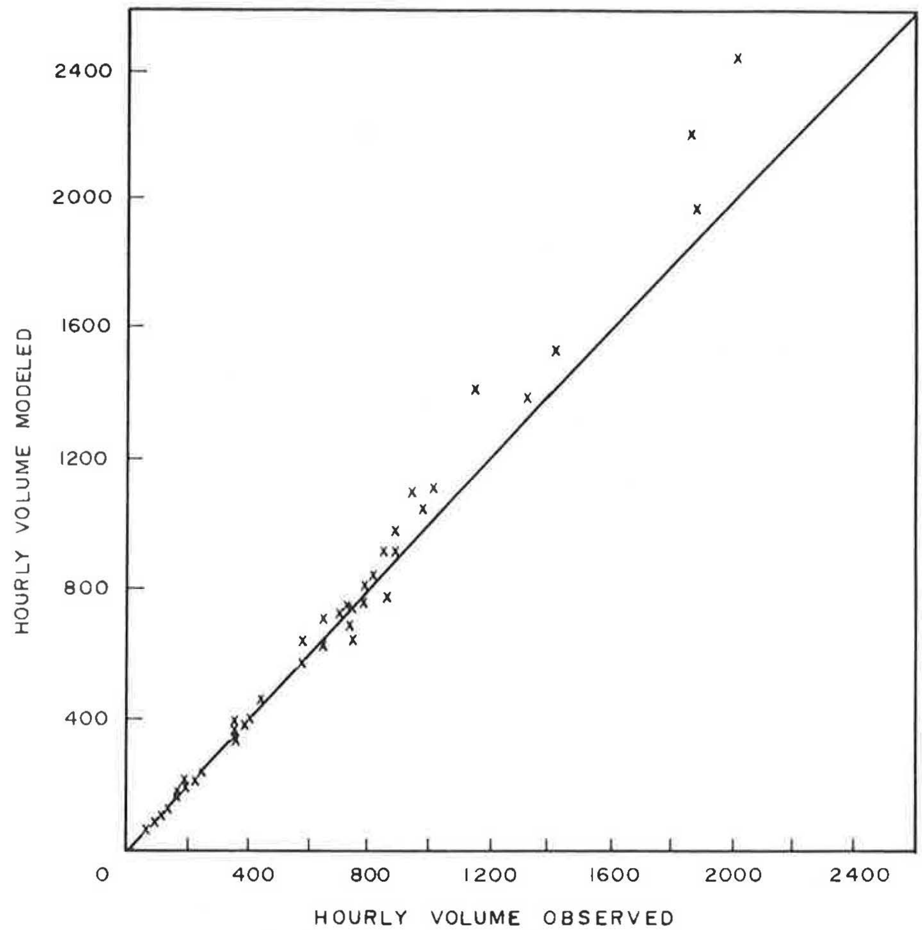

FIGURE 5 Comparison of actual counts and modeled values at the thirtieth highest hour.

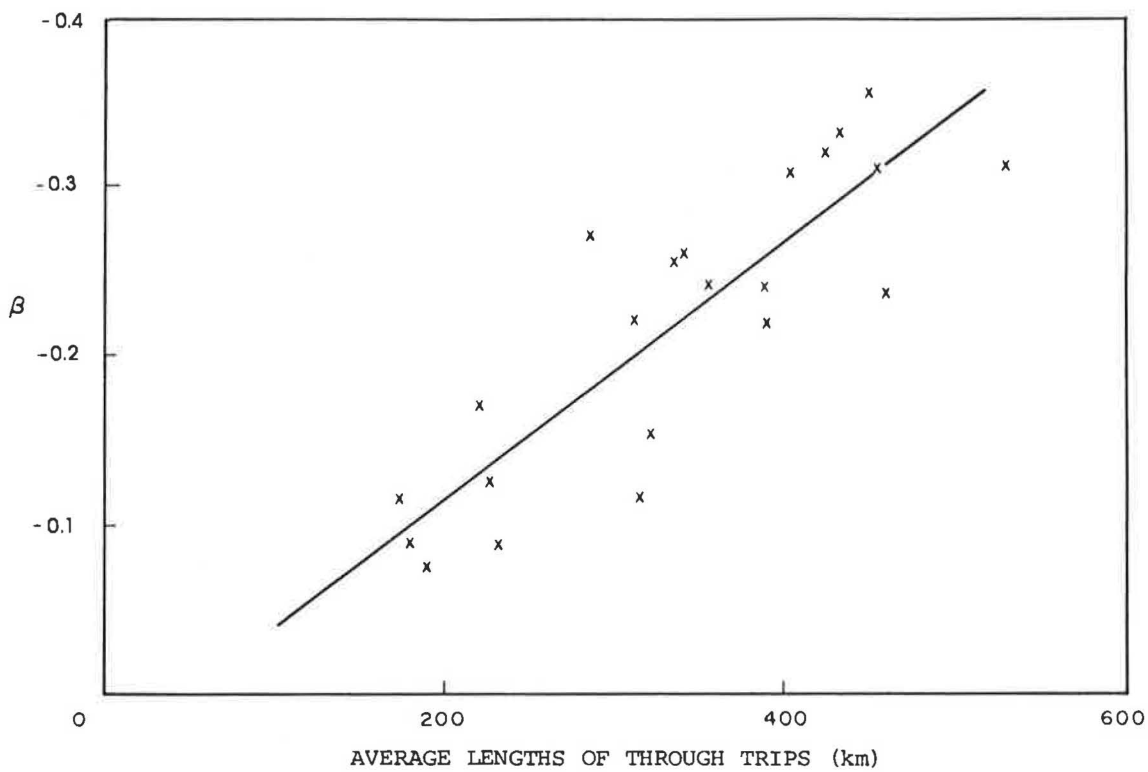

FIGURE 6 Relationship between β and the average length of through trips.

TABLE 2 RELATIONSHIP BETWEEN TRIP LENGTH AND β

Average Trip Length (km)	β	Comments
200	−0.12	Typical of roads with very little peaking
300	−0.19	Typical of the average rural road in South Africa
600	−0.42	Highest peaking roads in South Africa

other countries will in the future also provide interesting insights. The relationship between β and average trip length and the importance of trip length in selecting and classifying traffic counting stations provide avenues for further research. It is also within the bounds of probability that the economic evaluation procedure described in the preceding paragraphs could lead to new insights into the volume concept of design hour.

SUMMARY

A methodology has been developed by estimating the traffic volume in any ranked hour of a year. This methodology depends on no more information than is required for a thirtieth highest hourly volume estimation.

The methodology centers on the normalized relationship that was found:

$$F_n/F_o = (N/N_o)^{\beta}$$

or

$$U_n = F_o \cdot \mathrm{AADT} \cdot (N/N_o)^{\beta}$$

The existence of this relationship is of great importance to the road design engineer. It is furthermore believed that this relationship should form the foundation for future research on traffic volume variations and design hour volumes.

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