SPEED-FLOW RELATIONSHIPS ON CAPE TOWN FREEWAYS

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1. Introduction

The theory of traffic flow enables us to describe the relationship between flow, density and speed for all conditions of traffic flow on freeways. Unknown characteristics can be estimated once a particular relationship between two flow characteristics is known.

Speed-flow relationships are applied in many areas of transportation and traffic engineering. It has been used as a tool to determine design capacities for roads, to determine level of service for traffic flow (based on the *Highway Capacity Manual (HCM 2000 (1))* "Level of Service" concept), and to calculate travel costs on a specific road section.

Many researchers (2-12) have proposed models to describe the relationships between traffic flow characteristics on freeways. There are at least two approaches to the traffic flow problem. The microscopic approach (car-following theory) is concerned with individual vehicular speed and spacing, while the macroscopic approach deals with traffic-stream flows, densities, and average speeds. It has however been shown that these two approaches are interrelated (4).

2. Objective of the study

With the objective of testing the relevance of overseas models to South African conditions, a number of these models have been investigated with data obtained from South African freeways. Models obtained from three separate freeway sections on the N1 and N2 were compared to overseas models (1,15,18), as well as models obtained from local studies (16). The ability of each model to describe the entire data range was evaluated with the aid of statistical methods.

Also, in the belief that there are two regimes of traffic flow (9), namely uncongested flow and congested flow, separate curves were used to describe each regime. In this report, speed-flow relationships were also examined for individual lanes and compared to relationships established for average lanes, the objective being to determine whether the usual practice of averaging over all the lanes is in fact justified.

3. Traffic Flow Theory

3.1 Overview

Traffic flow is generally described and measured using three interrelated variables namely space mean speed U_s, volume (and/or rate of flow) Q, and density K. These variables are only meaningful when expressed in terms of averages over time and distance.

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Wardrop (2) established the following relationship known as the steady-state equation:

$$Q = U_S K \tag{1}$$

The basic relationships among the three parameters speed (U_s), flow (Q) and density (K) cited in Equation 1, assumes a linear relationship between density and speed. Figure 1 shows a generalised representation of these relationships, which are the basis for the capacity analysis of uninterrupted-flow facilities.
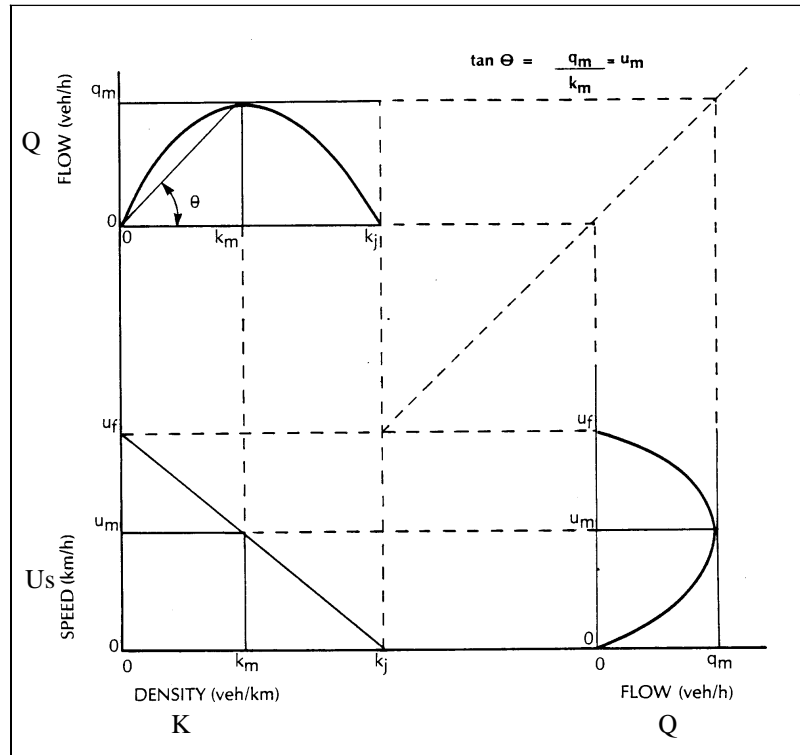

Figure 1: Generalised speed-, density-, and flow rate relationships on uninterrupted-flow facilities

The shapes and values of the above curves depend on the prevailing traffic and roadway conditions on the segment of road under study. It is important to note that it is unlikely that the full range of functions would appear at any study location. Survey data usually show discontinuities, with parts of these curves not present. A point where a discontinuity of the data usually occurs is the point where capacity (optimum speed U_m, optimum density K_m) of the particular freeway section is reached.

The single linear relationship between speed and density as illustrated in Figure 1 have been shown to be inadequate and several researchers have therefore constructed more complex models to describe this relationship. Some of the most pertinent traffic flow models have been investigated and will be discussed in the next section.

3.2 Empirical car-following models

3.2.1 Microscopic traffic flow theory

In order to describe vehicular flow in a microscopic manner, it was necessary to describe the motion of pairs of vehicles following each other. *Pipes (3)* formulated the expression:

$$x_n - x_{n+1} = L + S(\dot{x}_{n+1})$$ (2)

Where x_n = the position of the leading vehicle
x_{n+1} = the position of the following vehicle
L = the distance headway at standstill, including the length of the leading vehicle
S = the response time of the driver in the following vehicle

Differentiation of Equation 4 results in the basic equation of the car-following models:

Response = Sensitivity (λ) X Stimulus

Where *Stimulus* = Function of the difference in speed between two following vehicles.

Gazis, Herman, and Rothery (4) proposed a general expression for the sensitivity factor, λ:

$$\lambda = a \frac{\dot{x}_{n+1}^m(t+T)}{[x_n(t) - x_{n+1}(t)]^l}$$ (3)

Where a, m, and *l* = constants

Thus, the general expression for microscopic theories becomes:

$$\ddot{x}_{n+1}(t+T) = a \frac{\dot{x}_{n+1}^m(t+T)}{[x_n(t) - x_{n+1}(t)]^l}[\dot{x}_n(t) - \dot{x}_{n+1}(t)]$$ (4)

3.2.2 Macroscopic traffic flow theory

Macroscopic theories of traffic flow date back to 1935, when *Greenshields (5)* hypothesized that a linear relationship existed between average density and average space mean speed:

$$U_s = U_f\left[1 - \frac{K}{K_j}\right]$$ (5)

Where U_f = average free-flow speed
K_j = jam density

Other significant macroscopic models developed included exponential models, parabolic models and bell-shaped models. Some of these models are:

Greenberg (7) model: $u = c.\ln\left(\frac{k_j}{k}\right)$ (exponential) (6)

Underwood (8) model: $u = u_f e^{-k/k_0}$ (exponential) (7)

Drew (10) model:
$$u = u_f \left[1 - \left(\frac{k}{k_j} \right)^{\frac{n+1}{2}} \right] \text{ for } n > -1 \quad \text{(parabolic)} \tag{8}$$

Drake, May & Schofer (11) model:
$$u = u_f e^{-\frac{1}{2}\left(\frac{k}{k_0} \right)^2} \quad \text{(bell-shaped)} \tag{9}$$

Edie (9) hypothesized that there were two regimes of traffic flow: free-flow and congested flow. He proposed the use of an exponential speed-density relationship (Underwood model) for the free-flow regime, and the *Greenberg* model (Equation 6) for the congested flow regime.

3.2.3 Interrelationships between theories

A paper published by *Gazis, Herman, and Rothery (4)* in 1960 showed that several proposed macroscopic theories are mathematically equivalent to the general expression for microscopic theories (Equation 4), provided proper integers are selected for the exponents *m* and *l*.

It can be shown that the *Greenberg (7)* model (eq. 6) is obtained when m = 0 and *l* = 1, the *Drew (10)* model (eq. 8) is obtained when m = 0 and *l* = 3/2, the *Greenshields (5)* model (eq. 5) is obtained when m = 0 and *l* = 2, the *Underwood (8)* model (eq. 7) is obtained when m = 1 and *l* = 2, and the bell-shaped curve proposed by *Drake, May, and Schofer (11)* (eq. 9) is obtained when m = 1 and *l* =3.

May and Keller (12) developed a matrix of steady-flow equations for different *m* and *l* values. The matrix enables the utilization of non-integer m and *l* values, and consequently, expressions can be determined which more closely resemble actual speed-density relationships.

4. Data Acquisition

4.1 Requirements

Three representative sections were selected for study. In order to obtain accurate speed/flow curves, it was necessary to obtain representative data that covered the full speed/flow/density domain. To this end, it was needed to find appropriate sections where bumper-to-bumper conditions were reached in the morning, while it was also important to choose sufficient time-periods for study to ensure that all the degrees of congestion were covered.

Various factors influence driver behavior on a given stretch of road. These factors should be taken into account during section selection and should be reasonably consistent in order to ensure that the conclusions drawn from this report are applicable to other areas. These factors are roadway conditions, traffic conditions and others such as the weather and visibility.

Another important aspect was the ability to collect data accurately. In this study, data were collected with a video camera from fixed vantage points near each section under study. Therefore, for each section, the location of the vantage point as well as the choice of section length was very important to ensure that an adequate distance of road could be filmed.

4.2 Method

An observation of the traffic flow on each section of road during morning peak conditions warranted a study period of about 3 hours (06:00-09:00). The battery-life of the video camera only allowed for a single session of $1^1/_2$ h to be filmed on a given day. This meant that the study period had to be divided into two $1^1/_2$ h sessions on consecutive days. In order to eliminate the effect of weekend traffic, only Tuesdays, Wednesdays and Thursdays were considered for analysis.

During playback of the filmed footage for each section, each reference point used during the surveying (which was done during filming) was identified and marked on the television screen. These markers were used as distance beacons during speed and density measurements.

Average speed and density values for each lane were measured during 1-minute time intervals. Distinction was made between passenger cars, minibus taxis, trucks, and buses. During analysis for each section, adjustment factors (*Papacostas and Prevedouros (13)*) were used to convert heavy vehicles (trucks and buses) to passenger car equivalents (pcu's).

4.3 Location

4.3.1 Section 1
The N1 freeway near Century City is a 6-lane dual carriageway primarily carrying urban commuter traffic towards Cape Town during the morning peak period. The section under study is situated on the 3 lanes inbound towards Cape Town between the Wingfield interchange and the interchange connecting Sable Road to the N1. The speed limit is 120 km/h.

4.3.2 Section 2
The N1 freeway between Old Oak interchange and the Stellenberg interchange (R300) was investigated. Section 2 was located on the two lanes of the 4-lane dual carriageway inbound towards Cape Town with a speed limit of 120 km/h.

4.3.3 Section 3
The N2 next to Hazendal close to the Jan Smuts interchange where the M16 crosses the N2 was investigated. Section 3 was located on the three lanes of the 6-lane dual carriageway inbound towards Cape Town with a speed limit of 100 km/h. The right hand lane is reserved for buses and taxis during morning peak conditions in the form of an exclusive bus/taxi-lane. This lane is, however, not enforced and many other vehicles use it.

5. Data Analysis

5.1 Regression Procedure

Our equation for predicting the nature of the observed data depends on various unknown parameters. These parameters are again dependent on the type of model being fitted to the data and are estimated by the method of least squares, which minimizes the errors in predicting the observed data. The least square estimates of the parameters specifically minimize the sum of the squares of the residuals. The residual is therefore an estimate of the error for our prediction of the actual value.

The best models in each case were chosen on the basis of their overall ability to describe the speed-density data. In some cases, models were used in conjunction because of their ability to describe certain areas of the data well (while failing at other areas). In most cases, these models on their own failed to describe the whole range of the data well, resulting in relatively low R^2 values. As a result, specific models were selected to represent certain areas of data.

5.2 Models Utilized

The following models were used for analysis of the data acquired for each lane on each section during the given study period: *Greenshields* model, *Greenberg* model, *Underwood* model, *Drake, May and Schofer* model, Multi-regime Matrix model, and the Composite model. The best model obtained from the matrix of steady-flow equations developed by *May and Keller (12)* constituted the Multi-regime Matrix model. The Composite model is the final model, consisting of the best model obtained (in each case) for the free-flow regime in conjunction with the best model obtained for the congested-flow regime.

5.3 Results

5.3.1 Separate lanes

After careful consideration of the regression results, it was decided that the Greenberg model best described the congested-flow regime, while the Multi-regime model was used to represent the free-flow regime. Figure 2 is an example of the Composite model fitted to the right hand lane data of Section 1. Overall R^2 values close to 0.9 were obtained for each of the lanes of Section 1. This, together with the fact that a good representation of both the uncongested and congested data is achieved, leads the author to believe that the Composite model is very effective in describing traffic flow on Section 1.
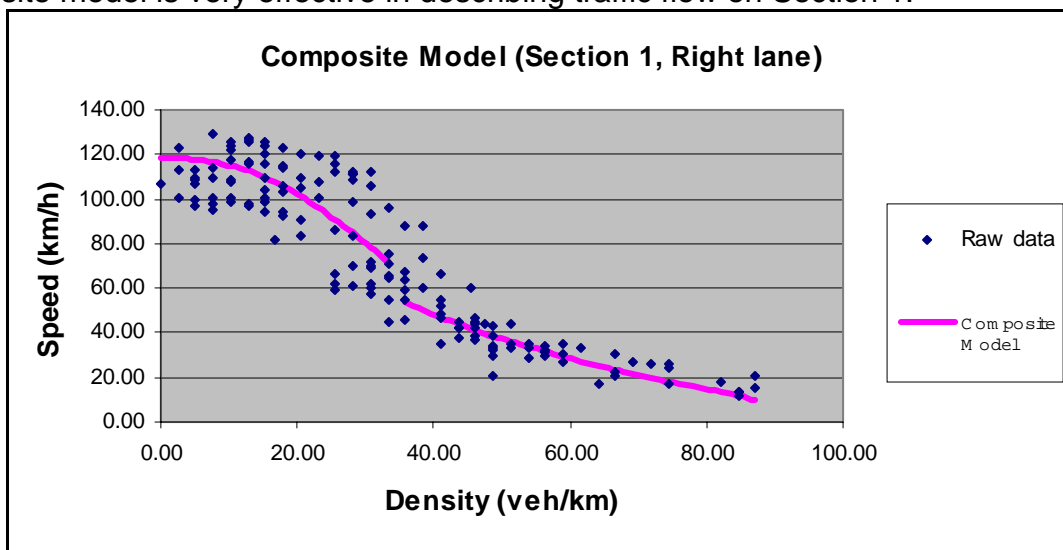

Figure 2: Composite model fitted to right hand lane data (Section 1)

Figure 3 is an illustration of the Composite model describing the speed-density relationship for each of the three lanes of Section 1.
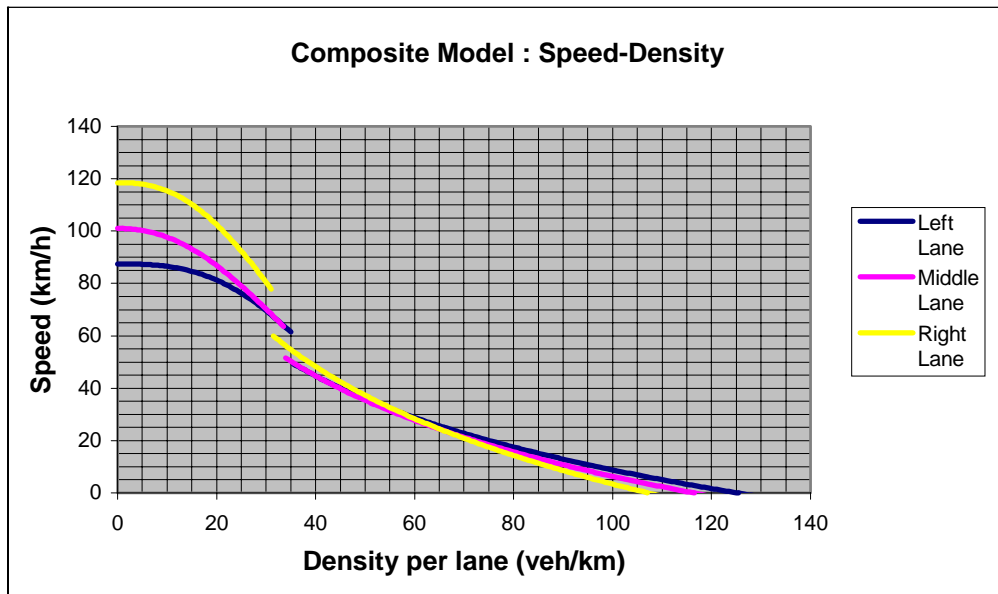

Figure 3: Speed-Density relationship for separate lanes (Section 1)

From the figure, we can clearly distinguish between the different lanes when looking at uncongested side of the graph. The difference in average speed between the three lanes decreases as the density increases. There is a very small difference between the three congested curves.

Bearing in mind that the Composite model consists of two separate curves for each lane, each with its own point where capacity is reached, a specific density value had to be chosen for separation between the uncongested and congested regimes. In this report, the separation point was chosen as the point where capacity is reached for the uncongested curves (Multi-regime curves). The corresponding density value was used as the separation point.

Once the Composite model for the speed-density relationships were established, the corresponding flow-density curves and speed-flow curves could be determined by applying the steady state equation (Equation 6).

5.3.2 Average lanes

The R^2 values obtained from the combined lane data are lower than the values obtained for the separate lanes. This is expected, since a single model is used to describe the speed-density relationship of all the lanes on a particular freeway section. Nonetheless, the R^2 values obtained for average lanes in this report are deemed satisfactory.

Figure 4 is an illustration of the Composite model describing the speed-density relationship for an average lane of each section.
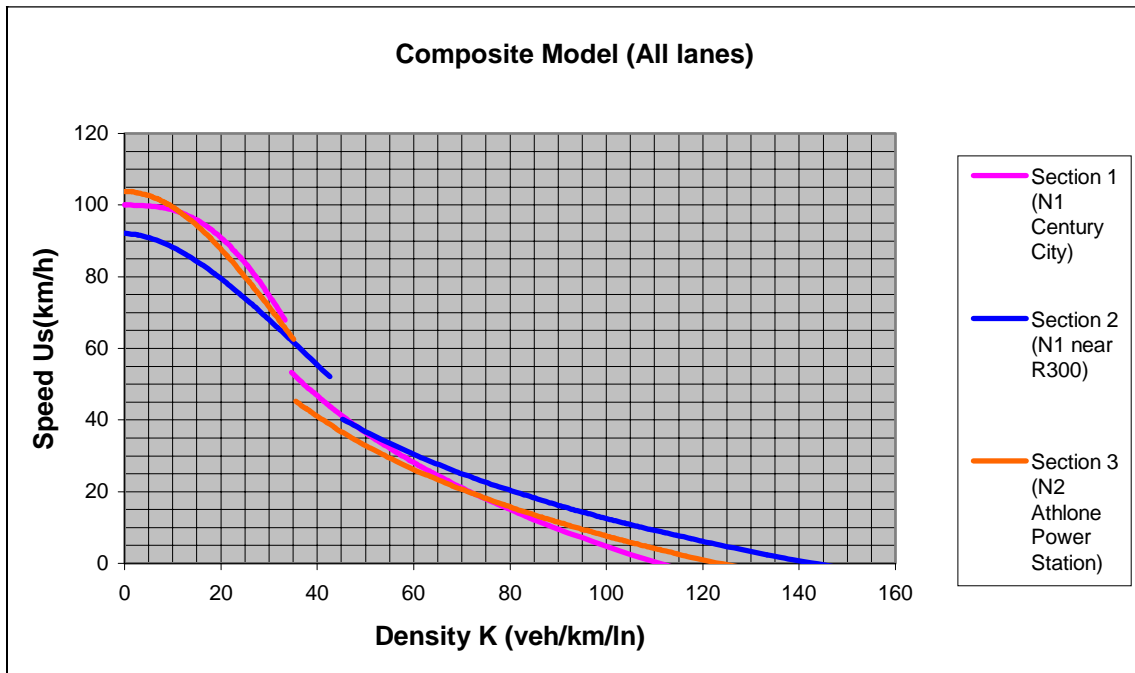
Figure 4: Speed-Density relationships for average freeway lanes

6. Comparison between Models

6.1 Individual lane Models

A study by *Hurdle, Merlo and Robertson (15)* focussed on individual freeway lanes in the USA. The study was based on data collected by the Ontario Ministry of Transportation (OMT) in 1991 and 1992 from two separate locations on Highway 401 (Toronto). The subject of the study was speed-flow relationships in uncongested conditions. Simple polynomial functions (as opposed to theoretical car-following functions) were fitted to the individual-lane speed-flow data.

Figure 5 is an example of the uncongested Composite curves compared to the polynomial curves for median freeway lanes (right hand lanes).
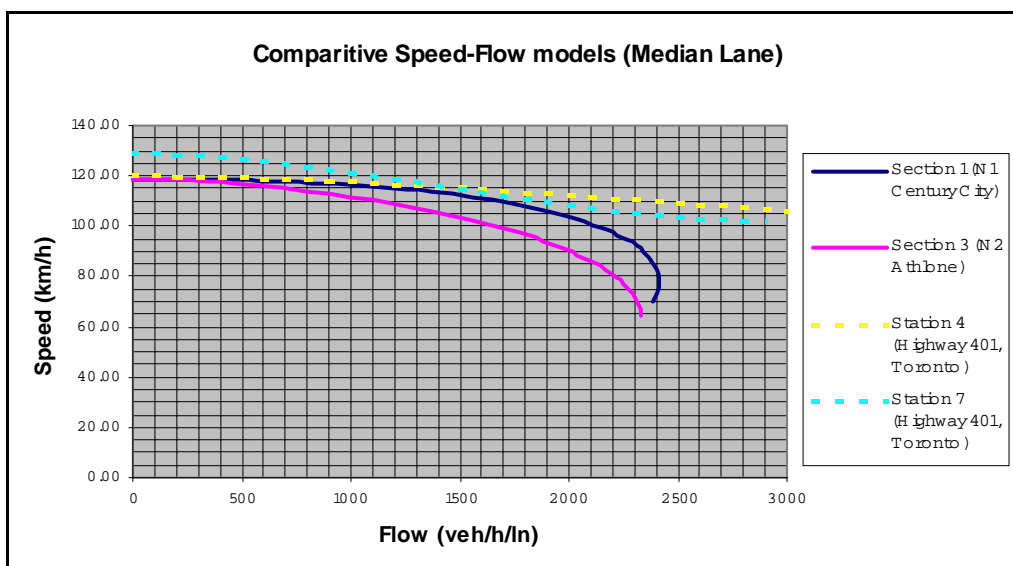

Figure 5: Comparative Speed-Flow models for Median freeway lanes

There are certain areas where the polynomial curves (Highway 401, Toronto) are very similar to the uncongested curves taken from the Composite model. It is however interesting to note that higher average speeds are estimated for the lanes of Highway 401. Also, as higher flows are reached, the speeds of the Composite curves decrease more rapidly towards capacity.

6.2 Average-lane Models for Uncongested conditions

Kruger, Kruger and Stander (16) of Bruinette Kruger Stoffberg Inc. compiled a report in 1988 for the Department of Transport (DOT). This report was commissioned by the National Transport Commission with the purpose of establishing specific speed-flow relationships as guidelines for application to South African conditions. Data was obtained from the Comprehensive Traffic Observation (CTO) project undertaken for the Department of Transport, which covered a number of local urban freeways and provided extensive information on traffic behaviour on these roads. DELTRAN curves (17) were used to analyse the data obtained from the CTO project. Different types of roads were categorized for uninterrupted facilities. Two of these types (relevant to this report) are urban and suburban freeways. Figure 6 compares the different DELTRAN models to the Average-lane Composite models.
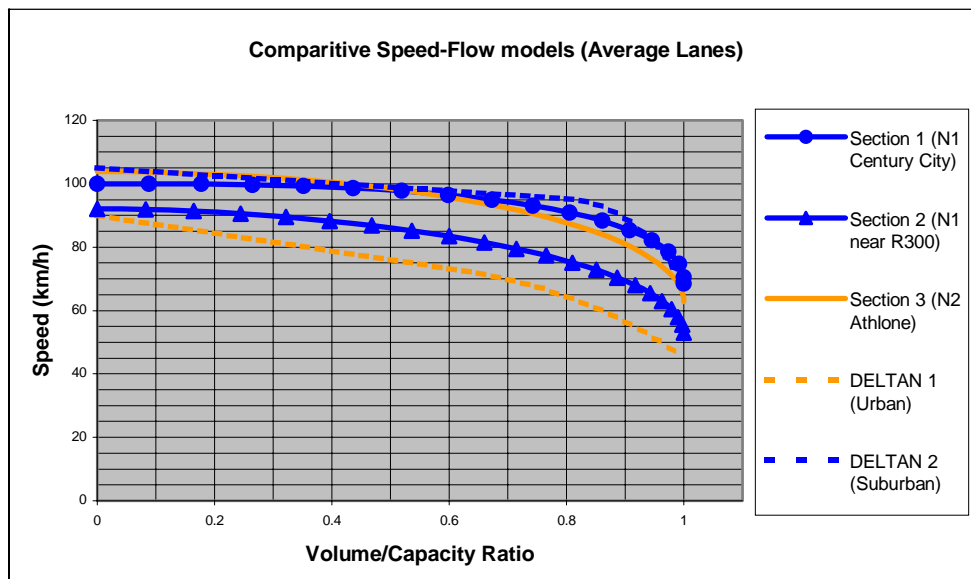

Figure 6: Comparison of Composite curves with DELTRAN curves

The Composite curve for Section 3 is very similar in shape to the DELTRAN 1 curve for urban freeways. However, there is a large difference in speed between the two curves, notwithstanding the fact that each of the freeway sections from which the two curves have been obtained operates with a speed limit of 100 km/h.

An extremely good correlation can be observed between the Composite curve of Section 1 and the DELTRAN 2 curve for suburban freeways. Although the Composite curve for Section 2 is very similar in shape (parallel) to the DELTRAN 2 curve, there is a large difference in speed between the two curves for the whole v/c range. Bearing in mind that each of the freeway sections from which the Composite and DELTRAN 2 curves have been obtained operates with a speed limit of 120 km/h, it is clear that Section 2 is occupied by slower moving traffic (on average). This can be explained by the fact that average travelling speeds on Section 2 were constrained by a rolling terrain and the fact that the section consisted of only 2 lanes (which resulted in less effective segregation between slower and faster moving traffic).

6.3 Other Average-lane Models for Congested conditions

Work was done by *Zhou and Hall (18)* with the purpose of investigating the relationship between speed and flow within congestion, that is, the lower portion of the speed-flow curve. Data were collected on separate days in 1997 and 1998 from the Gardiner Expressway and in 1998 from Highway 401 in Toronto (Ontario). Four types of functions were utilised: quadratic, cubic, exponential, and power.

Figure 7 is an illustration showing the differences between the congested speed-flow curves (average lanes) of the Composite model for each section and the curves represented by each type of equation.
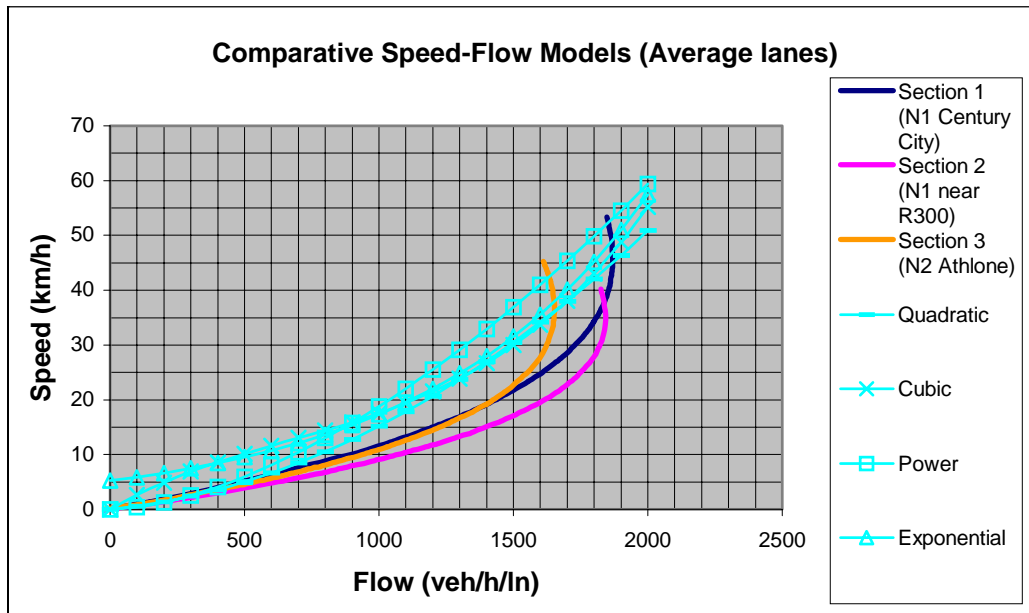

Figure 7: Comparison of Composite Speed-Flow curves with Overseas models (Congested)

There is a significant difference in shape between the Composite curves and the curves fitted to the Gardiner Expressway. Higher speeds are predicted by the Gardiner Expressway curves for most flows, suggesting that the Gardiner Expressway is a higher-quality facility.

7. Conclusions

(i)   There is merit for representing the whole range of speed-density data with two separate curves (uncongested regime and congested regime), as the Composite model yielded the best results in each case (based on optimum R^2 values and visual inspection).

(ii)   The models obtained in this report are based on data obtained during short time intervals on single days. It must be noted that the curves may vary considerably from time period to time period owing to changes in factors like traffic composition, weather conditions, day-night conditions, etc. Care must be taken in specifying the exact conditions under which particular data were captured.

(iii)   In most cases, the speed-density data are well represented at conditions of high congestion and low congestion. However, it is not possible to achieve an accurate representation the data near capacity, as the data are scattered (breakdown phenomenon).

(iv)   Separate lane curves differ considerably from each other (especially for the uncongested regime) for each freeway section.

(v)   The uncongested curves obtained from the N1 and the N2 freeways were similar in some respects to models obtained from overseas studies. However, higher capacities were consistently predicted by the overseas models. On the other hand, extremely good correlation was achieved between the uncongested curves and other curves obtained from South African studies. Similarly, overseas models were more optimistic with regards to flow on freeways during congested conditions. All in all, it seems that South African freeway conditions differ significantly from conditions in America (for both congested and uncongested regimes). It is therefore the opinion of the author that models obtained from overseas studies are in most cases not readily applicable to South African freeways.

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