THE OPERATIONAL ANALYSIS OF TWO-LANE RURAL HIGHWAYS

van As, S.C.[1] and van Niekerk, A.[2]

[1]Traffic Engineer.
[2]South African National Road Agency Limited.

ABSTRACT

A large proportion of the South African rural road network consists of two-lane highways. Some of these highways are carrying relatively high volumes of traffic with the result that some roads are operating at low levels of service. Currently, the Highway Capacity Manual of the Transportation Research Board is used for the analysis of the operations on these roads. Concern has, however, been expressed that the methodologies described in the HCM may not be appropriate or adequate for South African conditions.

An alternative model has been developed for the operational analysis of two-lane rural highways. This model utilises queuing theory to model platoons of traffic along a highway. The average platoon length is determined which can be utilised to determine evaluation criteria such as percentage followers and to predict travel speed. This model can also be used to model highways with wide shoulders where the shoulders are utilised by vehicles to provide passing opportunities.

The Highway Capacity Manual uses "Percent time spent following" as the measure of effectiveness in the evaluation of two-lane highways. This measure has the limitation that it can not readily be observed in the field. It is therefore proposed that this should be replaced by "percentage followers", although a new measure termed "follower density" should be used for the evaluation of two-lane roads.

1. INTRODUCTION

The majority of rural highways in South Africa consist of two lanes. Many of these carry relatively low volumes of traffic, but on some roads the traffic volumes are high with the result that the roads are operating at poor levels of service.

The operational analysis of two-lane highways is currently being undertaken by means of procedures provided in Highway Capacity Manual (TRB, 2004). Concern has been expressed that the methodologies described in the HCM may not be appropriate or adequate for South African conditions. If this is true, then it could have serious consequences in situations where capacity expansions are undertaken on the basis of inadequate analysis.

The aim of this paper is to describe a new model that was developed for the operational analysis of two-lane highways. A number of alternative models, such as the HCM model as well as various microscopic simulation models, were evaluated and various shortcomings were identified. The new model was extensively calibrated and validated by means of field observations. The model has been applied to a major rural two-lane highway (N4 between Belfast and Komatipoort) and was found to perform satisfactorily.

Proceedings of the 23rd Southern African Transport Conference (SATC 2004) 12 – 15 July 2004
ISBN Number: 1-920-01723-2 Pretoria, South Africa
Proceedings produced by: Document Transformation Technologies cc Conference Organised by: Conference Planners

One of the issues identified during the study is the measure of effectiveness used for the evaluation of two-lane highways. The Highway Capacity Manual uses "Percent time spent following", but this measure has the limitation that it cannot readily be observed in the field. It is therefore proposed that this should be replaced by "percentage followers", although other measures are discussed in this paper.

2. AVAILABLE MODELS

A number of alternative traffic models are available for the operational analysis of two-lane highways.

Three such models were identified and obtained for evaluation during the study. These models are the following:

- Highway Capacity Manual model (TRB, 2000)
- TRARR Microscopic simulation program (Hoban et al, 1991)
- TWOPAS Microscopic simulation program (FHWA, 2003; St John & Harwood, 1986)

The Highway Capacity Manual model is probably the best known of the available models. The model was developed by Harwood et al (1999) on the basis of field observations and simulation studies undertaken by the TWOPAS simulation program.

The TWOPAS program was specifically developed for the simulation of two-lane highways. The program was originally developed for the Federal Highway Administration by the Midwest Research Institute (the original name of the program was TWOWAF). The program was used in various research studies and further improvements and validations were made. Most recently, significant enhancements were made to the program as part of a project for developing the Highway Capacity Manual model. The program has also been incorporated in the Interactive Highway Safety Design Model (IHSDM) developed for the Federal Highway Administration.

TRARR is another program that was specifically developed for the simulation of two-lane highways. The program was developed for the Australian Road Research Board (now ARRB Transport Research) in 1985 and 1991. The program was one of two (the other being TWOPAS) which was considered as a basis for the development of the Highway Capacity Manual. An extensive evaluation by the University of California-Berkley indicated that TRARR and TWOPAS had similar capabilities. A problem with TRARR is that it is apparently no longer supported by the ARRB (McClean, 2003).

3. MACROSCOPIC SIMULATION MODEL

A new model that utilises macroscopic simulation techniques was developed during the study. This model applies queuing theory to simulate the change in queue or platoon length over the length of a road. The model consists of a number of modules aimed at calculating various aspects of traffic flow along a two-lane road.

Two of the important modules are the following:

- Free flow speed module. Free-flow speed is estimated as a function of parameters such as speed limit, intersections, pavement width, curve radius, road gradient and the acceleration and deceleration capabilities of vehicles.
- Platoon module. The change in platoon length is modelled over the length of the road. The platoon length depends on a variety of parameters such as traffic flow, speed differentials road width and other factors.

The length of a platoon (or moving queue) is the number of vehicles in the platoon, including the platoon leader. The minimum platoon length is therefore one. Percentage followers is directly related to the average platoon or queue length by the following relationship:

$$PF = 100 \cdot (N - 1)/N$$

in which PF is the percentage followers and N the average platoon length.

The platoon module models change in platoon length along a road in 20m intervals. The average platoon length is established at each of these intervals. A certain length is assumed at the start of the road, and a change in the length (ΔN) is modelled for each interval. The change is added to the length (N_i) at the start of the interval to determine the length (N_{i+1}) at the end of the interval:

$$N_{i+1} = N_i + \Delta N$$

The change in platoon length (ΔN) is determine as the difference of two components:

$$\Delta N = \Delta N_{Catchup} - \Delta N_{Overtake}$$

$\Delta N_{Catchup}$ is the increase in platoon length due to faster vehicles catching up slower vehicles while $\Delta N_{Overtake}$ is the decrease in the length due to overtaking of vehicles. Catching up occurs on both no-passing zones as well as passing zones, while overtaking would normally only occur on passing zones although it is possible to model "illegal" overtaking on such- zones. Where a wide shoulder is used for overtaking, the model provides for some overtaking on no-passing zones.

The increase in queue length due to catching up is calculated by means of a formula originally developed by Normann in 1942, simplified by Wardrop in 1952, and improved by Miller in the 1960's. Further adjustments were made during the project. The formula is as follows:

$$\Delta N_{Catchup} = \frac{\Delta D \cdot Z_i \cdot Q_i}{(1 - H_i \cdot Q_i) \cdot V_i \cdot \sqrt{\pi}}$$

In which

ΔD = Distance interval (20m)
Z_i = Speed coefficient of variation, depending on extent of queuing
Q_i = Flow rate in direction of movement (vehicles per second)
H_i = Average following headway (seconds), depending on vehicle composition
V_i = Average travel speed (m/s), depending on extent of platooning

The decrease in platoon length due to overtaking is calculated by means of the following formula developed by Miller (1960 - 1965):

$$\Delta NOvertaking = \frac{N_i - 1}{N_i} \cdot \frac{S_i}{V_i} \cdot \Delta D$$

S_i is the rate at which vehicles overtake from a long platoon of vehicles. Various researchers have developed various formulae for S_i that depends on gap acceptance and opposing flow. These formulae, however, are very difficult to calibrate. An alternative approach for estimating Si was therefore developed during the study.

The alternative method is based on the premise that, where it is possible, overtaking will take place at a rate higher than catch-up until such time equilibrium conditions are reached in which the overtaking rate is equal to the catch-up rate. Equilibrium conditions occur when platoon length no longer changes along the length of a road and $\Delta N_{Catchup}$ is equal to $\Delta N_{Overtaking}$. This means that Si can be determined using the following formula:

$$S_i = \frac{V_e \cdot N_e}{N_e - 1} \cdot \frac{\Delta N_{Catchup}}{\Delta D}$$

In which N_e is the equilibrium platoon length (this N_e is not a constant, it depends on traffic conditions). The reduction in platoon length due to overtaking can therefore be calculated as:

$$\Delta N_{Overtaking} = \frac{N_i - 1}{V_i \cdot N_i} \cdot \frac{V_e \cdot N_e}{N_e - 1} \cdot \Delta N_{Catchup}$$

The above formula therefore only requires an estimate of the equilibrium platoon length N_e to establish the reduction in platoon length due to overtaking. The advantage of the formula is that it is guaranteed to converge to the equilibrium platoon length, something that is very difficult to achieve with the original Miller model. Small errors in the catch-up and overtaking rates can accumulate and result in a large error in the platoon length estimation. The above approach reduces the possibility of such an error.

The Highway Capacity Manual (2000) provides a model for the estimation of the equilibrium platoon or queue length N_e that has the following form:

$$\frac{N_e - 1}{N_e} = e^{-Cons\tan t \cdot (Q_i + Q_j)}$$

in which Q_i and Q_j is the flow and opposing flow in the two directions of travel respectively.

An alternative model was developed in this study in which the equilibrium platoon length is estimated as follows:

$$N_e = 1 + Cons\tan t \cdot Q_i \cdot \sqrt{Q_j}$$

The main difference between the above models is that the HCM (2000) estimates equilibrium queue length as a function of the sum of the two opposing flows of travel, while the product of the two opposing flows of travel is used in the alternative model. The square root of the opposing flow is also used to reduce the impact of the opposing flow. The advantage of the alternative model is that it is sensitive to the directional split. At 0/100 or 100/0 directional splits, the average platoon length is estimated as one (no followers) which is conceptually more acceptable than the HCM model which does not converge to zero followers (except when flows are zero in both directions).

The model was extensively calibrated using traffic data obtained from TEL loggers as well as manual observations. The observations were undertaken under various conditions, on various types of roads and for various volumes of traffic. A variety of relationships were developed in addition to those described above and an attempt was made to take into account all possible and relevant factors that may affect flow on a two-lane highway. Due to the large number of factors and variables involved, it was not possible to calibrate all factors and some judgement was required to quantify these factors. Additional research would be required to calibrate all the identified factors. A problem encountered during the study is that there are not many two-lane roads available on which the required observations can be made. A major effort was required during the study to identify such locations.

4. MODEL EVALUATION

The different traffic flow models described above were evaluated by means of the following methods:

- Sensitivity analysis in which a model is evaluated to establish whether its predictions are logical and consistent.

- Comparison with other models with the purpose of identifying possible major differences.
- Comparison with observed traffic operations in which the model is applied to a particular road and situation and the predictions of the model are compared with observations of actual traffic operations.

A major problem that was identified with all currently available models is that none of them provide for overtaking in which the shoulder is used by the overtaken vehicle to move out of the way of following vehicles (as customary in South Africa). Observations made during the study indicated that the utilisation of shoulders has a major impact on traffic flow on a two-lane road. It would be possible to calibrate the Highway Capacity Manual model for such utilisation of shoulders, but the two microscopic simulation programs would require extensive rewriting of the program algorithms.

5. MICROSCOPIC SIMULATION MODEL EVALUATION

A problem with the microscopic simulation programs is that they require extensive calibration of factors that can not be easily observed in the field. Some factors involve human factors that can probably only be calibrated by means of a vehicle simulator. There are a number of factors, such as vehicle power-to-weight ratios, that can readily be calibrated by means of the field observations and some effort was made during the study to calibrate the TRARR program. In spite of such calibration, it was still not possible to obtain satisfactory correlation between the model and field observations.

One of the problems encountered with the TRARR program was that it becomes unstable when a long road section is simulated. For example, if a long no-overtaking section is simulated, the percentage followers first increase along the section (as expected) but then the platoons start breaking up and the percentage followers decrease. A further problem with the program is that it is apparently no longer supported by the ARRB (McLean, 2003). For these reasons, the program can not be recommended for general application.

Major problems were experienced with the version of the TWOPAS simulation program that was made available for evaluation during the study. The program continually terminated with error messages that could not be explained. It appears if the program has limited facilities for checking input data for possible errors with the result that invalid calculations are performed that lead to system errors.

One of the problems identified with the TWOPAS program is that it requires data in a pre-processed form. A further problem is that it uses imperial units such as feet, miles and pounds. This means that a front- and back-end program would be required to convert data to the format required by TWOPAS and to convert results produced by the program to a format that can be more readily be interpreted. Two such programs are available, namely IHSDM (FHWA, 2003) and UCBRURAL (Leiman & May, 1996). The IHSDM program was obtained but it was found to be somewhat cumbersome. It also did not eliminate all data errors with the result that TWOPAS still terminated with error messages. Due to its limitations with regard to the use of shoulders for overtaking, further attempts at getting the program operational were abandoned.

6. HIGHWAY CAPACITY MANUAL MODEL EVALUATION

The Highway Capacity Manual (TRB, 2000) model provides a relatively simple procedure for the analysis of two-lane highways. It would also be possible to extent the model to incorporate the effect of wide shoulders on overtaking. The manual, however, warns that there are situations that are too complex to evaluate by means of the model and that a traffic simulation model would be required for such situations. In practice, many problem two-lane highways that need capacity analysis are precisely those that are too complex for the model.

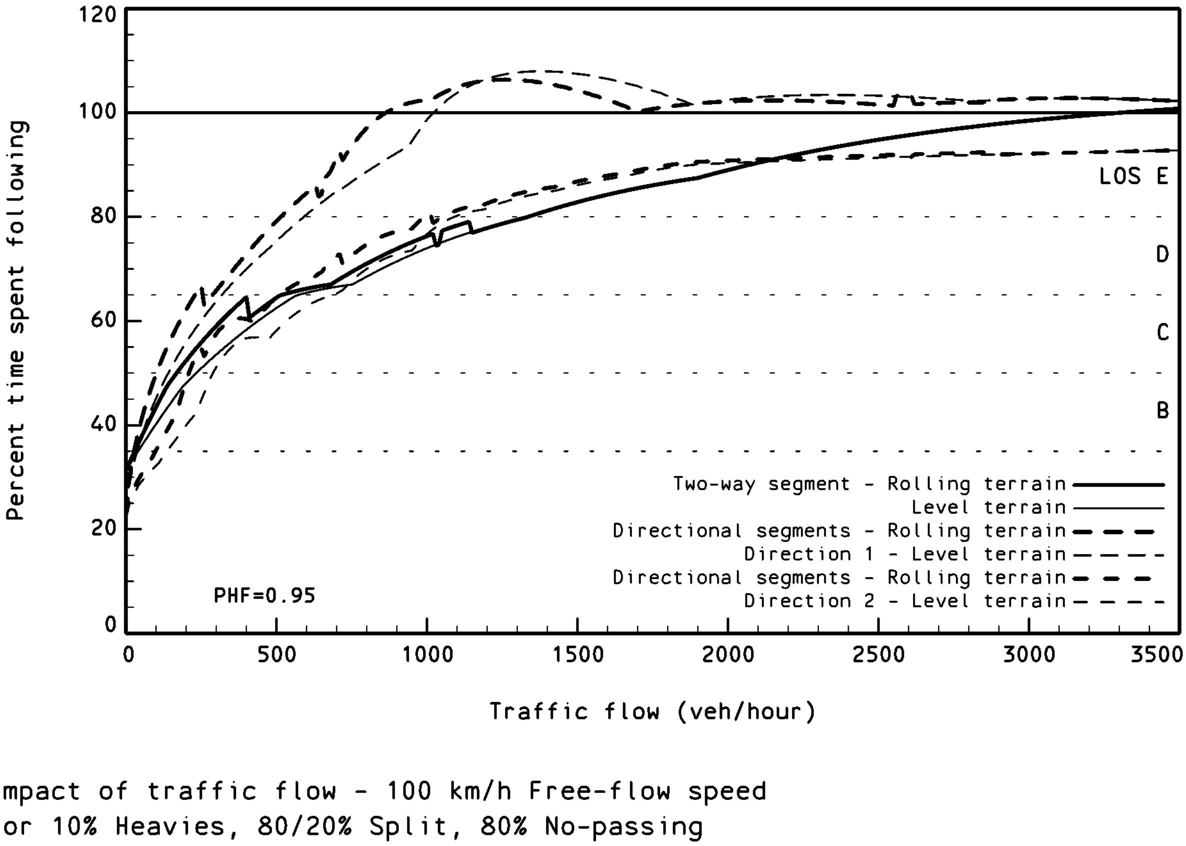


Figure 1. Sensitivity analysis of the HCM model - percent time spent following.

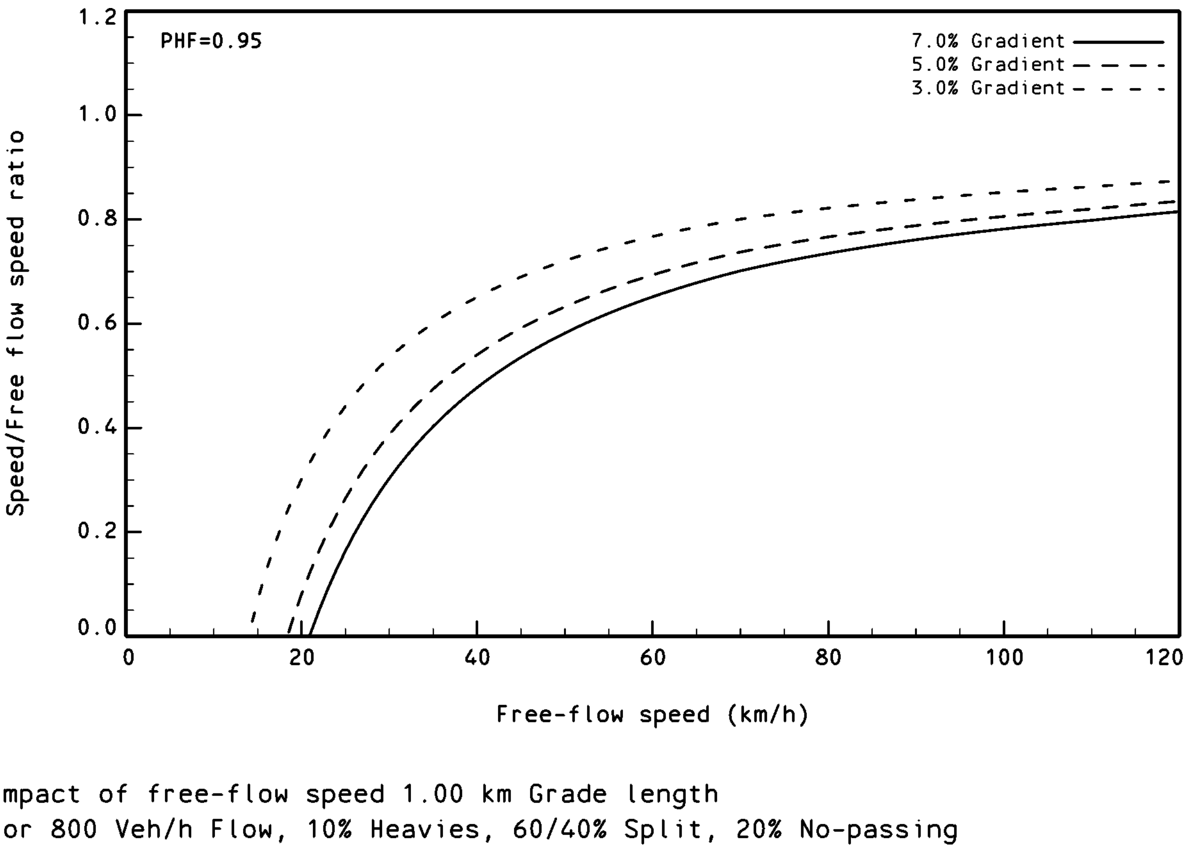


Figure 2. Sensitivity analysis of the HCM model - travel speed.

The Highway Capacity Manual was evaluated by means of a sensitivity analysis as well as comparisons with traffic observations. The sensitivity analysis, however, already indicated some serious shortcomings in the model. Some of the results of the sensitivity analysis are shown in Figures 1 and 2.

The following are a number of important problems identified in the figures:

- The HCM provides two alternative models or procedures for the analysis of two-lane roads, but the two procedures provide different results, as shown in Figure 1.
- The model produces a percent time spent following greater than 100% (as shown in Figure 1). This means that vehicles spent more time following than they are travelling.
- The percent time spent following is significantly greater than zero at zero traffic flow (see Figure 1). A zero or near-zero percent time spent following would have been more realistic.
- Average speeds are sometimes very low, and can even be negative when free-flow speeds are low such as on a steep upgrade. This problem is illustrated in Figure 2.

The above indicates that the model provided by the Highway Capacity Manual is not adequate to accommodate all variables and factors needed for the analysis of a two-lane highway. The model may be used in simple applications, but fails if the application becomes complex.

The macroscopic simulation model was extensively evaluated by means of a sensitivity analysis and comparison with observations and other models. Some of the results of the evaluation are shown in Figures 3 to 6. The model generally performed as expected while a fair comparison was obtained with traffic observations. No serious flaws were identified during the evaluation. Additional research would be required to calibrate all the parameters of the model, but it appears if the model can be used with some confidence in most practical applications.

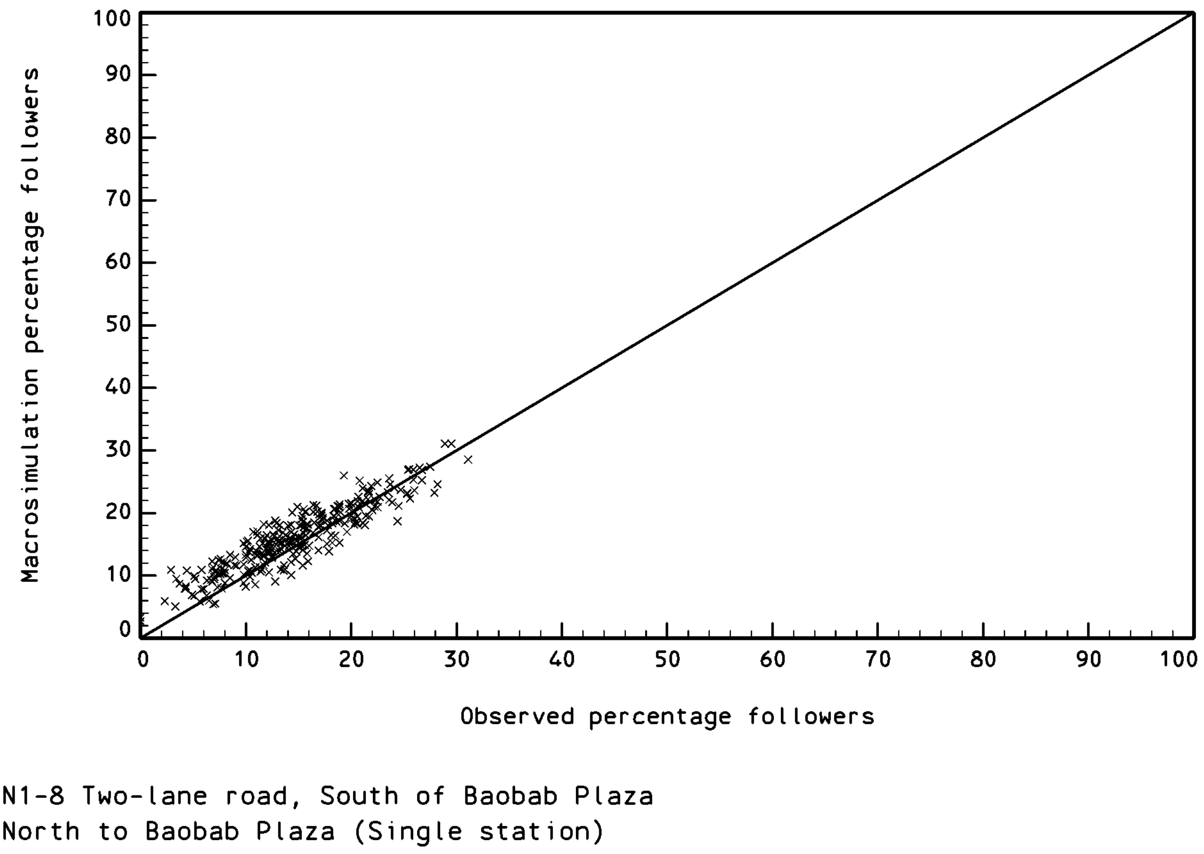
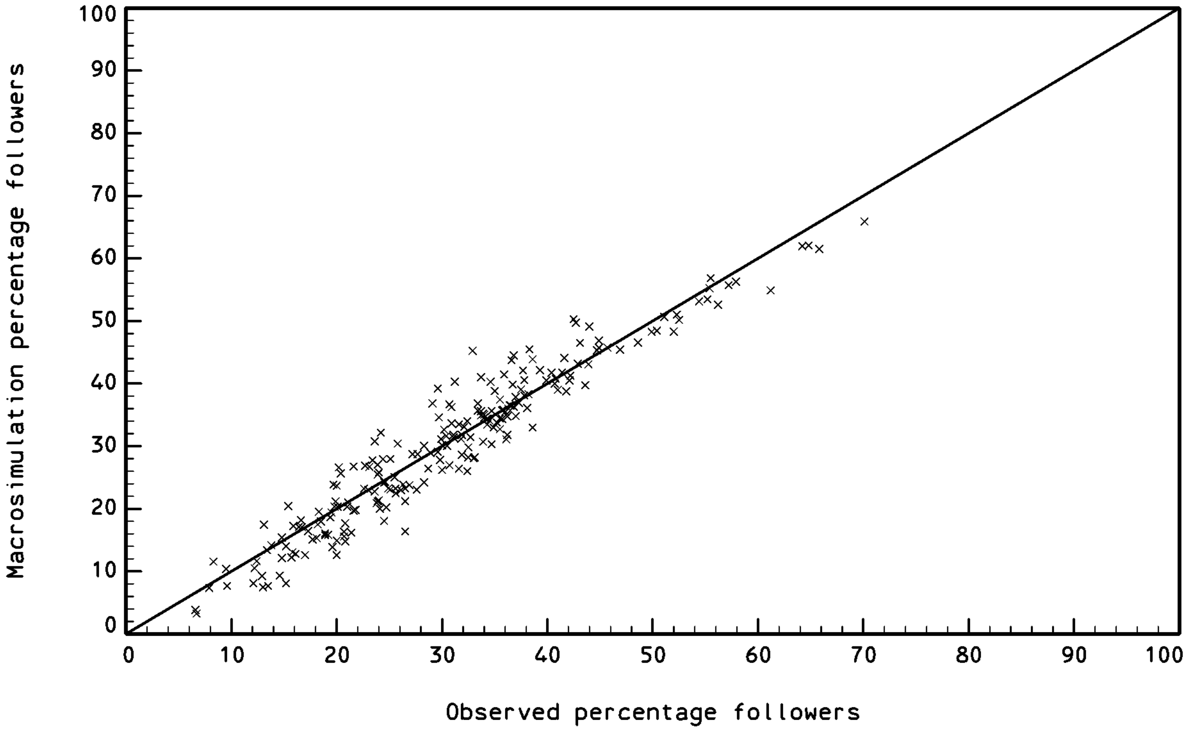
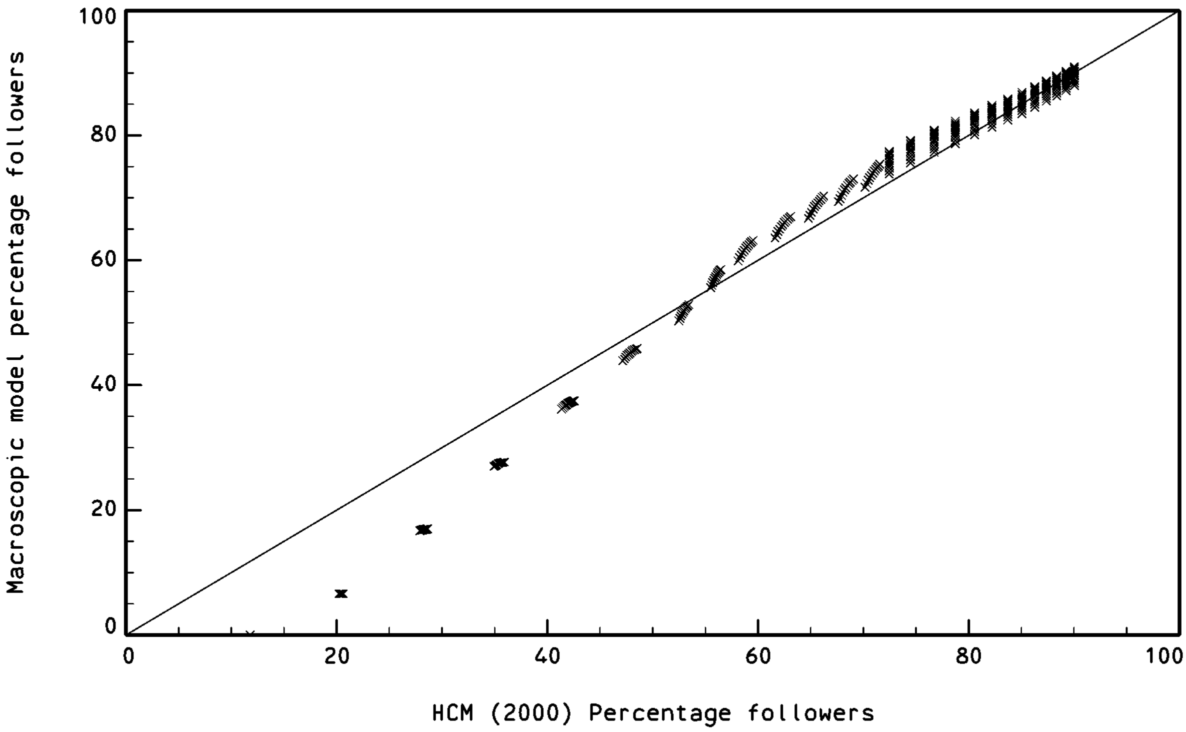


Figure 3. Comparison of macroscopic model with traffic observations (narrow shoulders).



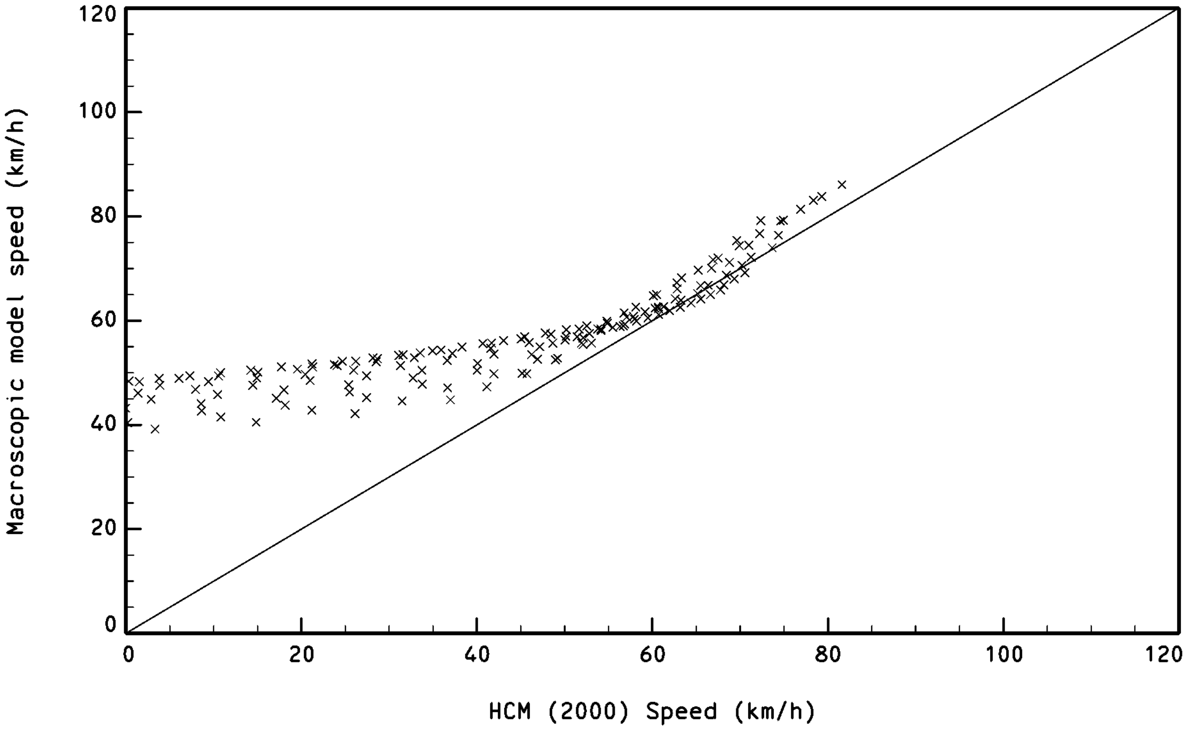
N4-32 Two-lane road, N4-5 Wonderfontein - Belfast, Km 25.4, 120 km/h
West to Pretoria

Figure 4. Comparison of macroscopic model with traffic observations (wide shoulders).



Comparison of HCM (2000) and Macroscopic model percentage followers
Extended segments: Level terrain with 20% No-passing zone

Figure 5. Comparison of macroscopic and HCM models - percentage followers.



Comparison of HCM (2000) and Macroscopic model speeds
Specific upgrade segments: 6.5% Gradient, 3.7m Lane, 0.5m Shoulders

Figure 6. Comparison of macroscopic and HCM models - travel speed.

A comparison of the macroscopic and HCM models is shown in Figures 5 and 6. Although a number of serious problems have been identified with the HCM model, it does not imply that the model is always inaccurate. There are situations in which the model provides fairly acceptable results. This is indicated in the figures that show that the two models agree fairly over a range of conditions, although there could be significant differences under certain conditions.

7. LEVEL OF SERVICE

The Highway Capacity Manual currently uses percent time spent following and speed as measures of effectiveness for establishing the level-of-service provided by a two-lane highway. Percent time spent following is defined by the manual as the "average percentage of travel time that vehicles must travel in platoons behind slower vehicles due to the inability to pass". In previous versions of the Highway Capacity Manual, it was called percent time delay, but was renamed in response to confusion regarding the meaning of the term (Harwood et al 1999). The new definition, however, is still not totally clear since it can be interpreted as either the "average percentage" or as the "percentage of average travel time". It appears if the manual uses the first interpretation, but this could not be clarified during the study.

A problem with percent time spent following is that it is difficult to measure in the field. The Highway Capacity Manual therefore allows the use of percentage followers as a surrogate measure for percent time spent following. Due to the complexities involved in measuring (and modelling) percent time spent following, it was decided to rather use percentage followers as the measure of effectiveness.

A further important issue that was identified with the use of many of the measures of effectiveness used by the Highway Capacity Manual is that they provide an indication of the level of service experienced by individual road users and not the total service provided to all road users. The problem with this approach is that level of service could be poor but the volume of traffic would be too low to warrant improvements. A norm based on the total measure of effectiveness established for all users would provide a better indication of when upgrading of a facility is warranted.

An example of the above issue can be found in the evaluation of traffic signal controlled intersection. The HCM uses average delay per vehicle as the measure of effectiveness in the evaluation of such intersections. This norm is then often used as the criterion for intersection upgrading. The new Volume 3 (Traffic Signal Design) of the South African Road Traffic Signs Manual (NDOT, 2001), however, uses average queue length as the warrant for the installation of traffic signals. This average queue length is directly related to "total delay" (in units of vehicle-hours per hour) rather than "average delay". A poor average level of service may be experienced at an intersection, but traffic signals would not be warranted when traffic volumes are low.

An interesting aspect of the HCM is that it uses traffic density as a measure of effectiveness in the evaluation of freeways. Traffic density is defined in terms of vehicles per kilometre of road (per lane), but is also directly related to "total travel time" (in units of vehicle-hours) per kilometre of road rather than "average travel time". Traffic density is therefore sensitive to the volume of traffic on a road.

An alternative measure of effectiveness was therefore developed during the study, namely "follower density". This measure is defined as the number of followers per kilometre per lane. The measure can relatively simply be calculated by means of the following equation:

$$K_F = P_F \cdot \frac{Q}{N \cdot U}$$

in which:

K_F = Follower density (followers per kilometre per lane)
P_F = Percentage followers
Q = Traffic flow in direction of travel
N = Number of lanes in direction of travel
U = Average (macroscopic) speed

Experience with the above measure of effectiveness indicates that it provides a relatively good indication of when capacity upgrading is warranted. It will only indicate a need for such upgrading when both a poor level of service is experienced and traffic volumes are high.

8. CONCLUSIONS AND RECOMMENDATIONS

The initial aim of the study was to evaluate alternative traffic models for two-lane highways. During the study, however, it was found that all available models had various shortcomings. A new model based on macroscopic simulation was therefore developed. No serious flaws have yet been identified with the model, although additional calibration of some of the model parameters would be required.

During the study it was found that percent time spent following or percentage followers only provide an indication of the level of service experienced by an individual road user, but that these measures cannot be used for purposes of warranting capacity upgrades of a road. An alternative measure of effectiveness, namely follower density was therefore developed which takes traffic volume into account. This measure provides a better indication of when capacity upgrading is warranted.

It is recommended that rural road authorities should start applying the model to all new designs as well as on existing roads on which traffic problems are being experienced. The model can even be useful in evaluating the design of roads that do not carry large volumes of traffic since it contains a module that checks the "design consistency" of a road. The model is relatively simple to apply and requires data that are normally available when a road is designed. At the time of the writing of this paper, the model has only been implemented in MS-DOS, but the plan is to extend the model to the Windows environment.

9. ACKNOWLEDGEMENTS

The paper is based on a research project of the South African National Road Agency Limited. Permission to use the material contained in the paper is gratefully acknowledged. The opinions expressed, however, are those of the authors and do not necessarily represent the policy or practice of the Agency.

10. REFERENCES

[1] Federal Highway Administration (FHWA), 2003, Interactive Highway Safety Design Model (IHSDM) Program manual, Turner-Fairbank Highway Research Center (TFHRC), McLean.
[2] Harwood, D.W., A.D. May, I.B. Anderson, and L. Leiman, 1999, Capacity and quality of service of two-lane highways, National Cooperative Highway Research Program, Transportation Research Board, National Research Council.
[3] Hoban, C.J., G.J. Fawcett and G.K. Robinson, 1991, A model for simulating traffic on two-lane rural roads, User guide and manual for TRARR Version 3.2, Technical Manual ATM 10B, Australian Road Research Board, Victoria, Australia.
[4] Leiman, L., and A. D. May, 1996, UCBRURAL: A User-friendly Interface for Rural Highway Computer Simulation Model with Emphasis on the Incorporation of the TWOPAS Model, Report No. FHWA/CA/TO-96/25, California Department of Transportation.
[5] McLean, J, 2003, Personal correspondence received. Project leader - TRARR development.
[6] Miller A.J., 1960, A mathematical model for the study of road traffic flow. PhD thesis, Manchester.
[7] Miller A.J., 1961, A queuing model for road traffic flow, J. Royal Stat. Soc., 23B(1), 64-75.
[8] Miller A.J., 1963, Analysis of bunching in rural two-lane traffic, Op. Res., 11, 236-247.
[9] Miller A.J., 1965, Queuing in rural traffic, Proc. Third International Symposium on the Theory of Traffic Flow, 122-137.
[10] National Department of Transport, 2001, Volume 3: Traffic signal design, South African Road Traffic Signs Manual, Pretoria.
[11] Normann O.K., 1942, Results of highway capacity studies, Public Roads, 23(4), pp 57-81.
[12] St. John, A.D. and D.W. Harwood, 1986, TWOPAS Programmer's Guide, Federal Highway Administration.
[13] Transportation Research Board (TRB), 2000, Highway capacity manual (Metric units), National Research Council, Washington, D.C.
[14] Wardrop J.G., 1952, Some theoretical aspects of road traffic research, Proc. Instn. Civ. Engnrs., 2, 325-362.

THE OPERATIONAL ANALYSIS OF TWO-LANE RURAL HIGHWAYS

van As, C.[1] and van Niekerk, A.[2]

[1]Traffic Engineer.
[2]South African National Road Agency Limited.

BIOGRAPHY

Alex van Niekerk has a postgraduate qualification in Transportation Engineering. He is employed by the South African National Roads Agency (Ltd) (North) where he is Divisional Head for Toll and Traffic. He is responsible for toll feasibility studies, toll operations, traffic engineering and geometric engineering.

He serves as committee member on the PIARC C1.4 committee for Network Operations and is a board member of the South African Society for ITS (SASITS).