A QUEUING APPROACH TO SPEED-FLOW RELATIONSHIPS ON FREEWAYS

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

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

ABSTRACT

Speed-flow relationships have traditionally been used to describe non-interrupted traffic operations on basic freeway segments. Such relationships typically show that when traffic flow is stable, speed reduces as traffic flow increases up to the maximum flow or capacity of the freeway. However, when traffic flow is unstable, the inverse of the above relationships is obtained.

In this paper, an innovative approach to the traditional speed-flow relationship is discussed. It is shown that the traffic on freeways can be analysed in terms of travelling queues or platoons. The queue or platoon lengths are dependent on the traffic flow and it is therefore possible to develop queue length - flow relationships. Speeds can be related to the queue length and it is therefore possible to develop speed-queue relationships. The combination of these relationships provides the traditional speed-flow relationship.

The advantage of the queuing approach is that it can be used to explain and clarify many of the operational characteristics of freeways. Queues or platoons form because of speed differentials between fast and slow vehicles. Faster vehicles therefore travel at lower speeds in these queues with the result that the average speed of the traffic stream reduces. Long queues create the problem that any disturbances along a freeway typically result in shock waves within the queues and in unstable flow. Various factors can contribute to such unstable flows, such as accidents and other incidents. Mostly, however, unstable flow occurs typically at interchanges where large volumes of traffic enter the freeway or where queues of traffic spill back from the interchange onto the freeway. Unstable flow can also occur on steep upgrades on which climbing lanes have not been provided.

1. INTRODUCTION

The speed-flow relationship is probably one of the most well-known and important relationships in the field of traffic engineering. It forms the basis for the capacity analysis of traffic facilities such as freeways, multilane roads and other. The relationship finds important application in the Highway Capacity Manual (TRB, 2000).

The speed-flow relationship provides an excellent overall or macroscopic description of the traffic stream. There are, however, a number of disadvantages in using the relationship. One of these is that the relationship can practically only be used for modelling relatively stable flows with the result that it can not readily be used to model changes in the flow of traffic over the length of the road.

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A further disadvantage is that due to its macroscopic nature it cannot be used to explain questions such as the following:

- Why does speed reduce as flow increases? Is it because drivers travel slower due to perceived danger of accidents at high flows, or because of speed differentials (or both)?
- What is the cause of unstable conditions on freeways?

In this paper, an alternative approach to the traditional speed-flow relationship is discussed. The approach is still macroscopic but it includes queue or platoon length as an additional traffic characteristic. It is shown that queue length can be related to traffic volume, while speed in turn is related to queue length. These relationships can be used to answer questions such as those posed above. There is also a possibility that the approach can be used for the modelling of flow over the length of a road, but further research is required to confirm this.

2. TRADITIONAL FLOW RELATIONSHIPS

Traditionally, traffic flow has been studied in terms of the following three so-*called fundamental characteristics* (Van As & Joubert, 2002):

- Flow Q (in units of veh/hour or veh/second)
- Speed U (in units of km/h or m/s)
- Density K (in units of veh/km or veh/m)

The following *fundamental relationship* exists between these three characteristics:

$$Q = U \cdot K$$

If any two of these three characteristics are known, the third is uniquely determined. The relationship can be visualised as a three-dimensional space, but it is more convenient to show the relationship as an orthographic projection in two dimensions, as shown in Figure 1.

The following terms are also shown in the figure:

- Qm the maximum flow rate
- Um the speed when flow rate is a maximum
- Km the density when flow rate is a maximum
- Uf the free flow speed when flow tends to zero
- Kj the jammed density when vehicles are stopped

The fundamental relationship shown in Figure 1 has the following specific characteristics:

- As density approaches zero (light traffic), speed approaches the free flow speed Uf and flow approaches zero. If there are no vehicles (K = 0) there can clearly be no flow (Q = 0) and the flow-density curve must therefore pass through the origin. Speed is at the maximum value (free flow speed Uf).
- As density approaches the jammed density Kj, both speed and flow approach zero. The jammed density occurs when all vehicles are stopped and flow is zero.
- For some value of the density between the two limits above, the flow must have one or more maximum values Qm corresponding with density Km and speed Um. Usually there is only one such maximum Qm that may be called the capacity of the road under prevailing conditions.

Flow conditions with densities less than Km, the density at which flow is a maximum, are normally considered to be stable conditions. Unstable conditions occur at densities greater than Km. The capacity of the road Qm which occurs at the density Km is of great interest being relevant both in the design of new facilities and in the efficient use of existing ones.

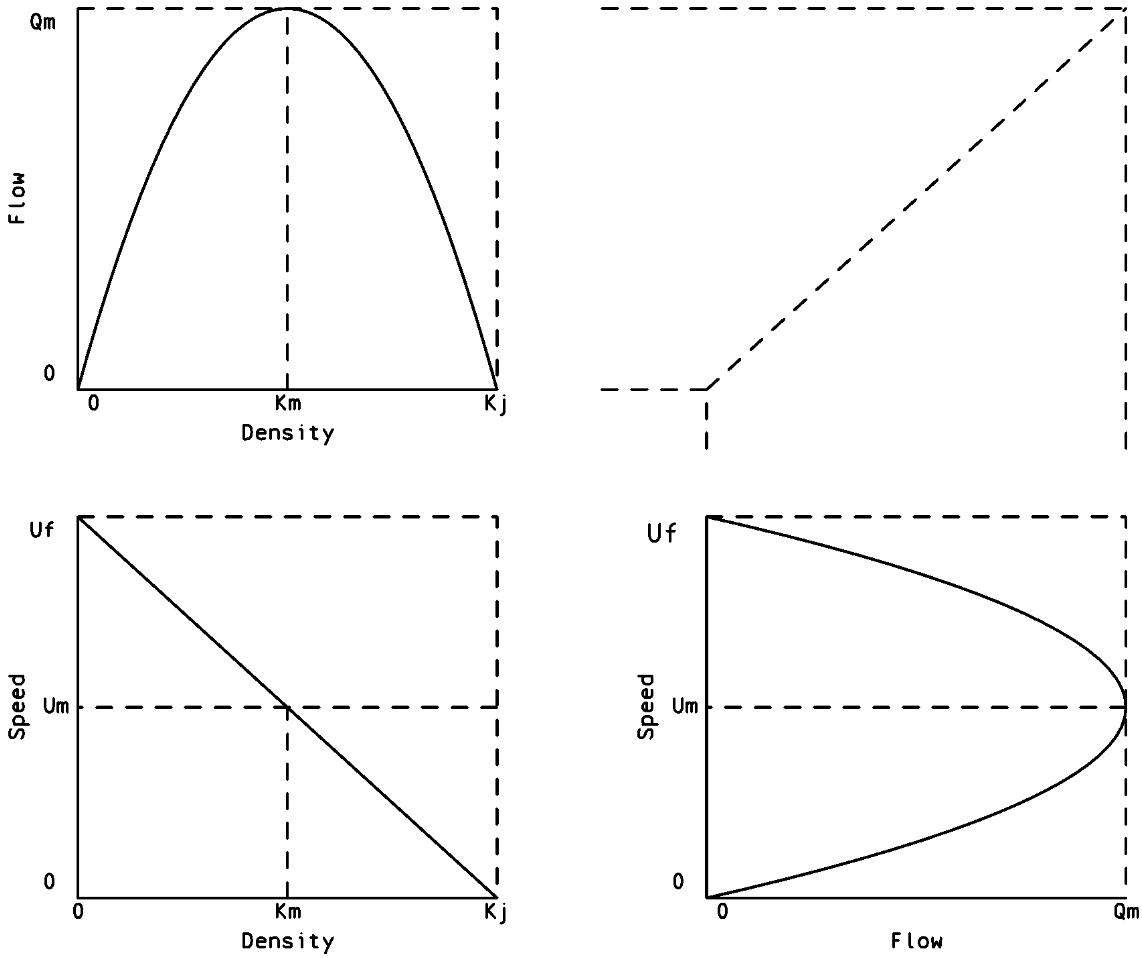

Figure 1. Traditional flow relationships.

3. QUEUE (PLATOON) LENGTH

Queue or platoon length is defined as the number of vehicles travelling in a travelling queue or platoon. The first vehicle in the platoon is termed the platoon leader, while other vehicles are followers. The queue length includes the platoon leader, and the minimum queue length is therefore one vehicle.

A vehicle is considered to be a follower when it is impeded by a preceding vehicle. In practice, it is difficult to identify such vehicles, and a maximum following headway is therefore used as a criterion to define a vehicle as following or non-following.

The 2000 Edition of the Highway Capacity Manual (TRB, 2000) uses a maximum following headway of 3.0 seconds. The 1985 Edition of the Manual has used a maximum headway of 5.0 seconds. Hoban (1984) proposed a value of 4 seconds based on observations in Australia. Joubert (1988) has evaluated a comprehensive range of headways in South Africa and has also recommended a 4-second criterion to distinguish between followers and non-followers.

An investigation was undertaken with the purpose of establishing the maximum following headway from field observations. Electronic equipment was used to measure headways but headways were manually classified as following or non-following. The study indicated that a 3.5 second headway is more appropriate for the definition of followers. This headway was used to establish the average lengths of queues for the purposes of this study.

4. FLOW RELATIONSHIPS INCORPORATING QUEUE LENGTH

Possible flow relationships that incorporate queue length as an additional parameter are shown in Figure 2 (see Appendix). The relationships are based on the assumption that queue length increase as traffic flow increases, up to a maximum queue length when traffic flow is at a maximum. The relationships with queue length are only shown for stable conditions since research is required to establish the form of the relationships when flow is unstable.

The relationships shown in the figure have the following characteristics:

- As density approaches zero (light traffic), speed approaches free-flow speed, flow approaches zero and queue lengths are short (minimum of one).
- As density increases on the road, but flows are still stable, speed reduces and mean queue length increases. At some value of the density, flow rate reaches a maximum and queue length is also at a maximum.

The original relationships shown in Figure 1 can be obtained if the relationships given in Figure 2 are combined and queue length is eliminated from the equation. The relationships involving queue length therefore does not replace the traditional relationships - but simply augment the relationships with the purpose of providing a better understanding of underlying causes.

5. OBSERVED FLOW RELATIONSHIPS

In order to test whether the hypothesised relationships in fact occur, traffic data were obtained from various freeways and the queue-length relationships analysed. The traffic data were collected by means of TEL traffic loggers and observations were made of each individual vehicle. The speed and arrival time of each vehicle were observed and vehicles were classified as following or non-following using the 3.5 second maximum headway criterion.

A few examples of the observed flow relationships are shown in Figures 3 to 6 (see Appendix). The figures show only the observed data points (for each 15-minute period of observations) and no attempt was made to fit a mathematical equation to the data. Additional research would be required to develop such a model.

The purpose of the graphs shown in Figures 3 to 6 is to illustrate that it is possible to explain traffic flow on freeways in terms of queue length. On some freeways, the relationships are relatively strong, especially when traffic flows are stable. Under unstable conditions, the relationships are less clear and show some degree of scatter. It is, however, clear that queue length is an important parameter in the modelling of traffic flow on freeways or multilane roads.

6. QUEUE FORMATION AND FLOW CHARACTERISTICS

The incorporation of queue length as a traffic flow characteristic provides an opportunity for explaining a number of observed traffic characteristics.

The two specific questions posed at the start of the paper can be answered as follows:

- The observed reduction in speeds as flow increases is probably due to two reasons. The first is that drivers may generally drive slower when traffic flow increases. A second, probably more important, reason is that faster vehicles are following slower vehicles in platoons or queues of vehicles, with the result that average speed is reduced. The formation of queues is the result of speed differentials and reduced overtaking opportunities at high traffic flows.
- Unstable flow conditions can to a great degree ascribed to the queues of traffic. The reason for this is that many drivers travel at relatively short following headways in the queues which do not provide sufficient time to react to disturbances along a roadway. Any instability in traffic flow not only propagates down the length of a queue, but also tends to amplify with the result

that traffic flow becomes unstable. Such instability has little impact on traffic flow when queues are short, but become significant when queues are long.

The above discussion illustrates an important advantage of incorporating queue length as one of the traffic flow parameters, namely that of explaining some important flow characteristics, something which was not possible with the traditional flow relationships. This indicates that there is some possibility that queue length can be used to model traffic flow along a freeway, but additional research is required to confirm whether this would be possible.

7. QUEUE LENGTH AND LEVEL OF SERVICE

The Highway Capacity Manual uses the concept of level of service (LOS) as a measure of the operational conditions within a traffic stream. The level of service provides an indication of driver comfort and convenience, freedom to manoeuvre, traffic interruptions, travel time and speed. Although speed is a major consideration for many drivers, it is more likely that freedom to manoeuvre and the degree of impedance caused by other vehicles is of greater concern to drivers.

The Highway Capacity Manual uses traffic density as the measure of effectiveness for determining level of service on freeways. Although density is an excellent measure of effectiveness, it has the disadvantage that density may not be directly related to the degree of impedance experienced by vehicles. The traffic density may be high on a road, but this does not automatically indicate that a high level of impedance is experienced by traffic.

This above problem with traffic density is illustrated in Figures 3 to 5 (see Appendix). These figures show that for the same traffic density, average queue length may differ from road to road. For a traffic density of 20 vehicles per lane per kilometre, the average queue length in the three figures varies between approximately 6.5 and 10.5 vehicles per platoon. The impedance on the road with an average queue length of 6.5 vehicles must be significantly lower than the road with a queue length of 10.5 vehicles, even if the traffic density is the same. It is also more likely that traffic flow could become unstable on the road with the longer queue lengths.

An alternative measure of effectiveness that addresses the above problem is "follower density". This measure is defined as the number of followers per lane per kilometre of road. The number of followers is established as those vehicles following at headways shorter than 3.5 seconds. For the example discussed above, the follower density would be approximately 16.9 for the road with an average queue length of 6.5 vehicles, and 18.1 for the road with a queue length of 10.5 vehicles. The follower density is therefore higher on the roads in which a higher degree of queuing occurs.

8. CONCLUSIONS

The above analysis was undertaken with the main purpose of indicating that some of the flow interactions can be explained in terms of one additional flow parameter namely queue length. Queue length can be used to explain questions such as why speed reduces when flow increases and why traffic flow becomes unstable when traffic flow increases.

The queue length approach has the potential of being applied in a traffic model in which changes in traffic flow along a length of road can be modelled. This potential must, however, be further investigated and additional research is required.

A further advantage of incorporating queue length, is that it allows for the definition of a measure of effectiveness which directly accounts for level of impedance experienced by traffic on a freeway. A follower density can be defined which directly provides for queue formation on freeways.

Additional research is required to confirm many of the concepts described in this paper. Such research would require extensive field observations of traffic flow on freeways with different characteristics. Mathematical models describing the relationships also need to be developed. The results of such research would enhance the understanding and analysis of traffic flow on freeways.

9. REFERENCES

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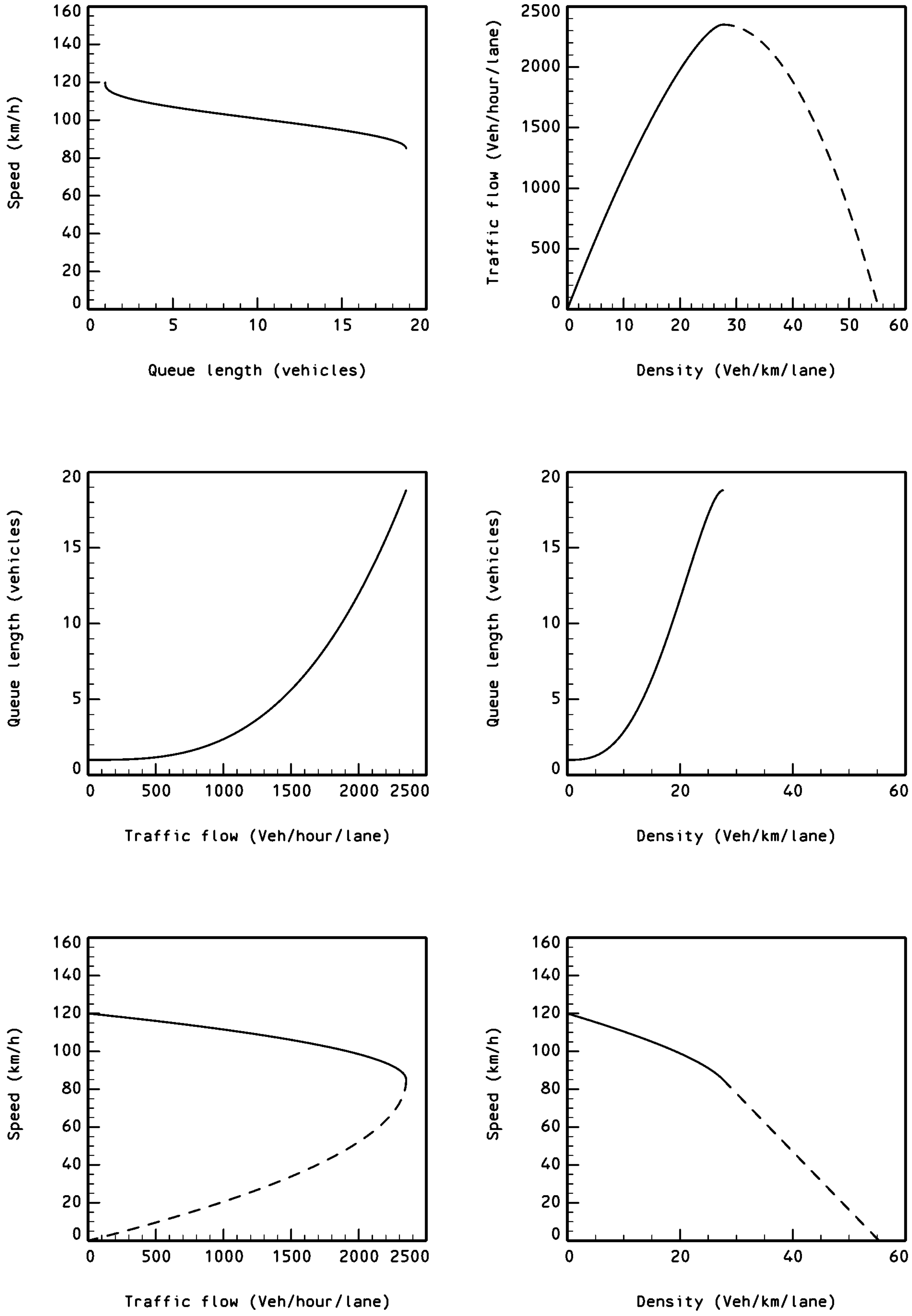
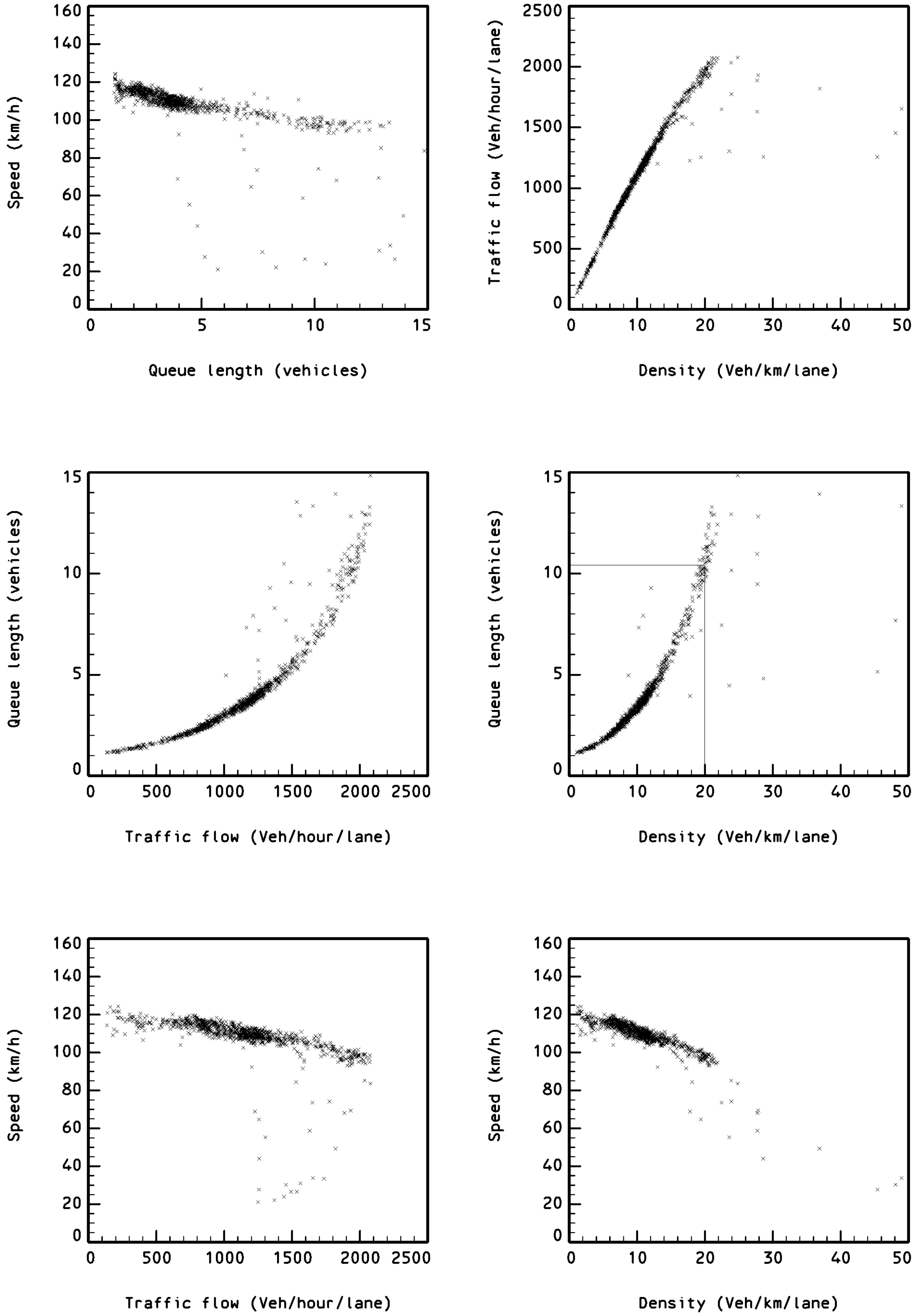
Appendix



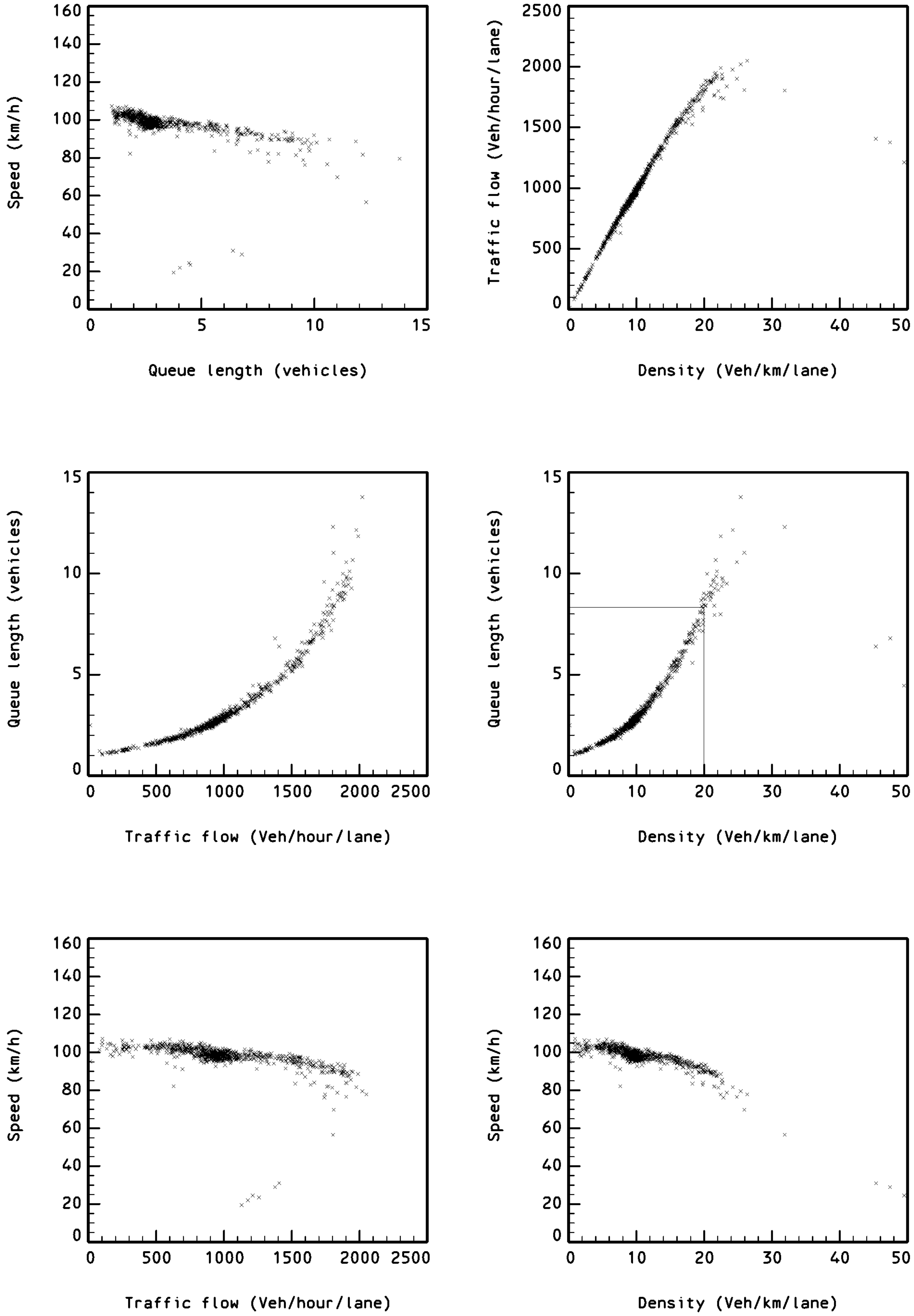
Traffic flow relationships

Figure 2. Traffic flow relationships incorporating queue lengths.



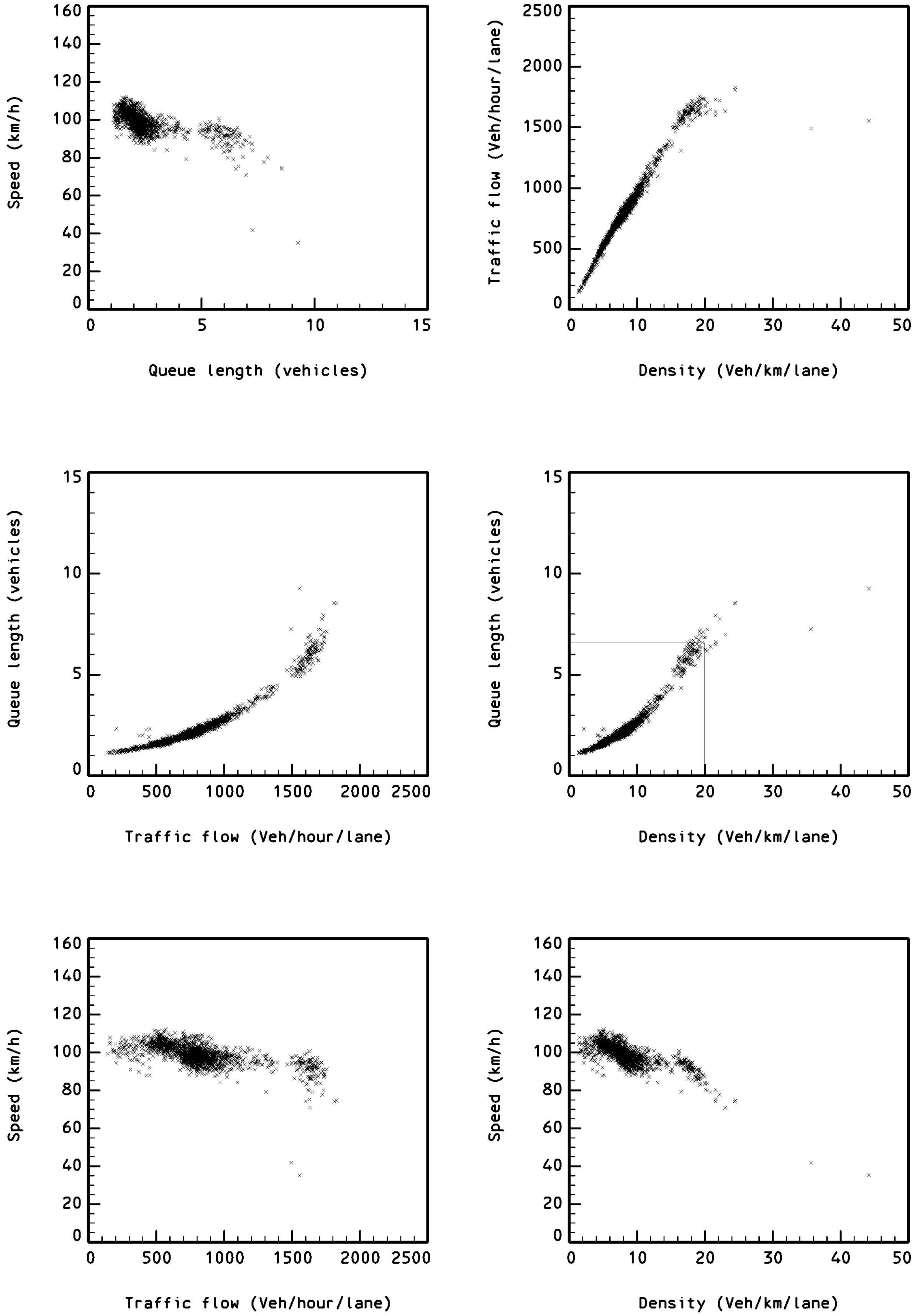
N1 Freeway, Km 6.4, South of Old Johannesburg Road, 120 km/h, Flat gradient
Southbound direction (To Johannesburg)

Figure 3. Example observed flow relationships - N1 freeway near Old Johannesburg Road.



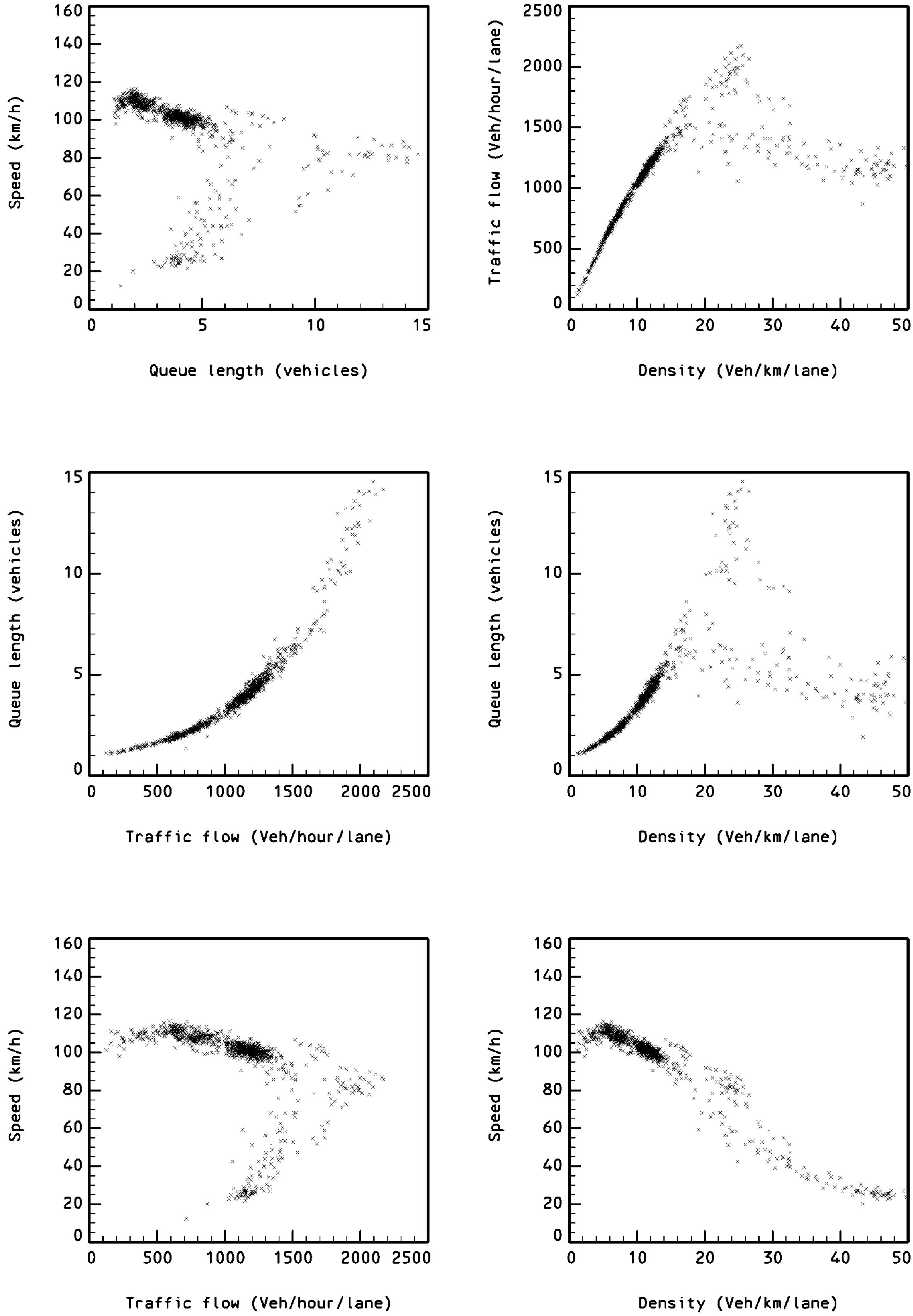
N1 Freeway, Km 17.8, Jean Avenue, Centurion, 100 km/h, Flat gradient
Northbound direction (To Pretoria)

Figure 4. Example observed flow relationships - N1 freeway near Jean Avenue.



R59 Freeway, Between Michell and Swartkoppies, 120 km/h, Flat gradient
Northbound direction (to Johannesburg)

Figure 5. Example observed flow relationships - R59 freeway.



N1 Freeway, Km 1.2, North of New Road, 120 km/h, Top of gradient
Southbound direction (To Johannesburg)

Figure 6. Example observed flow relationships - N1 freeway near New Road interchange.

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BIOGRAPHY

Dr Christo van As is a transportation engineer specialising in traffic and safety engineering. He is currently a specialist consultant for ITS Consulting engineers and is also a part-time professor at the University of Pretoria where he was involved since 1980 in the presentation of the post-graduate subjects such as Traffic Flow Theory and Statistical methods.

He has completed a number of research reports for various organisations, including the National Department of Transport and the South African National Road Agency. He is a co-author of the Volume 3, Traffic Signal Design of the Road Traffic Signs Manual as well as the National Guidelines for Road Access Management in South Africa. He has also recently completed a major research study on the capacity of rural two-lane highways on which the presentations are based.

In 2000 he received the Chairman's award of the Division Transportation Engineering of the South African Institute of Civil Engineering for contributions to the profession.