PROBLEMS OF INSTRUMENTATION IN CAR-FOLLOWING RESEARCH

R-74-2
Voorburg, 1974
Institute for Road Safety Research SWOV, The Netherlands

CONTENTS

FOREWORD

In order to regulate motor traffic flow such that multiple collisions can be prevented, it is necessary to know how motor vehicle drivers follow each other in traffic. This so called "following-behaviour" or "car-following" needs to be measured and subsequently analysed. As no efficient measuring technique had been developed, the Institute for Road Safety Research SWOV included in its programme a project to fill this gap. The research was directed to examining the following-behaviour of drivers unaware that an experiment was being conducted.

Documentation research was carried out and operating requirements were drawn up to specify the performance of such instrumentation. It is now apparent that no apparatus has yet been developed that could enable car-following research, such as was contemplated, to be carried out with any degree of success. Developing such apparatus is very costly and success cannot be guaranteed. SWOV have therefore terminated the project. The findings may nevertheless be of use in research along similar lines, now or in the future, depending on improved apparatus becoming available. The project has shown ways of further studying of possibilities of reducing irregularities in motor vehicle following-behaviour. Part of the present programme is directed to discovering the relationship between intrinsic danger and traffic volume, and the relationship between traffic volume and speed. The approach to the problem of motor vehicle following-behaviour now includes studies into perception and information by the driver (analysis of the driving task).
This report was written by ir. H. Botma, Department of Theoretical Research, Pre-crash Projects.

Ir. E. Asmussen, Director
Institute for Road Safety Research SWOV, The Netherlands

SUMMARY

In theory, research into following-behaviour in real traffic is possible by means of an instrumented vehicle in traffic which records its own longditudinal movement and that of any randomly chosen following vehicle.

Analysis of this measuring problem shows that for measuring the relative movement of the following vehicle, Doppler radar has the most suitable characteristics, but still falls short of requirements. Unless development of satisfactory apparatus is attempted, the conclusion to be drawn is that research into traffic flows will have to be restricted to the recording and analysis of less detailed data than accelerations and decelerations of individual vehicles.

I. INTRODUCTION

After pilot investigations it was decided to begin the project "Traffic flow models for traffic arteries" by research into following-behaviour in single lane traffic. The observational method chosen for this is the recording by means of an instrumented vehicle of the following behaviour of randomly selected road users who are unaware of any experiment. The background to this choice is given briefly in the following.

As a starting point it is proposed that many traffic situations can be described by means of three basic patterns:
a. single lane traffic along traffic arteries;
b. merging of two traffic flows into one;
c. splitting of a single stream into two.
Case a. is considered first as it is the simplest.

Single lane traffic flows can be approximated by a number of mathematical models. The simpler of these describe the behaviour of a single car as a consequence of the behaviour of the directly preceding vehicle (car-following). The more sophisticated models attempt to describe entire traffic flows.
It has been decided to start with research into car-following models which may be considered to be of relevance to practical traffic safety research, especially when bearing in mind nose-tail and multiple collisions. Moreover, knowledge of following-behaviour may be of use in constructing more sophisticated models which give a fuller description of traffic flow.
For the subsequent step the method chosen is research into car-following in real traffic with drivers unaware of the experiment. Other possibilities are:
1. Extending the existing models further and running simulations with them, e.g. Fox & Lehman (1). This was not considered to be a useful approach as the verification of many sorts of sub-models is lacking and the relevant parameters are unknown.

2. Laboratory research using driving simulators, e.g. Wallner (2). The problem here is in generalising these results to real traffic situations.
3. Investigations carried our in real traffic, but using test drivers, e.g. Rockwell et al (3). This has already been done on a large scale and has yielded results. But here as well the generalisation to the real traffic situation is difficult due to the uncertainty of whether the test drivers behaved "normally" in the experimental situation.

The chosen line of research forms, as it were, the concluding step to the above mentioned possibilities 1, 2 and 3.

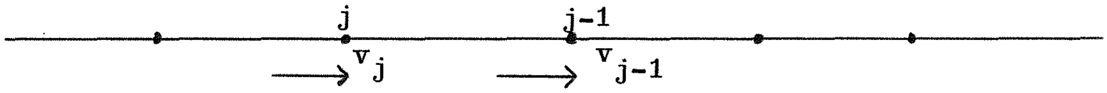
Feasible techniques for measuring following-behaviour are: aerial photography, the use of sensors on the road, and the use of an instrumented vehicle.
Pilot investigations into the use of aerial photography have shown that it is probably impossible to determine accelerations of individual vehicles, which is necessary for research into car-following models, with sufficient accuracy. Reports from Ohio State University (4) and Breiman (5) have confirmed this impression. This does not mean, however, that this method cannot be applied to any research into traffic flow.
Neither can sensors on the road record the paths of individual vehicles with suffient accuracy for their variations in speed to be determined.
The only remaining possibility is the instrumented vehicle in which use can be made of measuring techniques such as radar and lasers which have undergone rapid development and improvement during recent years.

This report is limited to a survey of the possibilities of obtaining data from an instrumented car participating in normal traffic, and using this data to test car-following models.

II. CAR-FOLLOWING MODELS

1. General

Given a stream of vehicles moving along a carriageway and only considering movement parallel to the direction of the road (longitudinal movement) is equivalent to imagining the vehicles represented by points or dashes moving along a line.



Vehicle j follows vehicle j-1 at a distance which varies with time. The driver tries to avoid colliding with the preceding car and, in many cases, also tries to avoid letting the separation become so great that he is not affected by the behaviour of the preceding vehicle.

The car-following models attempt to describe this "following-behaviour" and proceed from the assumption that it can be explained to a large extent by the movements of the preceding vehicle. It can also be stated that vehicle j responds to the behaviour of vehicle j-1 and this can be formulated as: response = sensitivity times stimulus.

The response is taken to be the resultant of the accelerator and brake pedal operation: the acceleration (or deceleration). The most important stimulus would seem to be the difference in speed between the two vehicles. Sensitivity is taken to be constant in the simpler models, whereas in the more sophisticated ones it is taken to be a function of mutual separation and speed of the vehicle being studied.

A vital factor in these considerations is the time it takes the driver to observe, process the information, decide and act. This time, plus the delay inherent in the vehicle, is combined in a single "response time" τ . We have the following model:

$$a_j\ (t + \tau) = F(v_r(t),\ v_j(t),\ x_r(t),\ p) \qquad (3.1.)$$

$a_j\ (t + \tau)$ = acceleration v_j at time $t + \tau$

$v_r(t)$ = relative speed = $v_j(t) - v_{j-1}(t)$

$x_r(t)$ = mutual separation = $x_j(t) - x_{j-1}(t)$

τ and p are parameters of the model; p can comprise a number of parameters.

In this form it is not necessary to differentiate between stimulus and sensitivity.

Example:
One of the most simple models is:

$$a_j(t + \tau) = \lambda v_r(t) \qquad (3.2.)$$

With slightly more detail:

$$a_j(t + \tau) = \mu v_r(t)\ x_r(t)^{-\alpha}\ v_j(t)^{\beta} \qquad (3.3.)$$

where $p = (\mu, \alpha, \beta)$

2. Discussing the models

It is hardly to be expected that models of the above sort will fully describe following-behaviour. What is of importance is the degree to which it is achieved. It may be expected that models of this sort primarily describe oscillations about an equilibrium value. In order to describe processes such as the rapid approach of a vehicle towards the vehicle preceding it, the starting up from standstill of a line of vehicles, the forced slowing down to a standstill of a line of vehicles, the models will have to be modified to a greater or lesser extent.

Even if it is assumed that following-behaviour is chiefly determined by the externally perceptible characteristics of the preceding vehicle, the following points may be raised.

1. Behaviour is the same for acceleration and deceleration.

In fact there is a difference and this could be reflected in the values of the parameters.

2. The effect of the brake-lights is absent.

This objection can also be met by making parameters of the state of the brake-lights dependent ones.

3. Driver observation is a continuous process.

This is incorrect; furthermore the interval between observations is not constant. It seems difficult to introduce this effect into the model.

4. The driver responds to infinitely small changes by infinitely small responses.

This effect can be taken account of by threshold levels and discrete responses.

5. No account is taken of limitations of the acceleration available.

This factor can be included, taking also into account the fact that the upper and lower limits are different functions of speed and road surface (see for example Lewis (6)).

6. The model is entirely deterministic.

The change element can be accommodated in the parameters and/or in an extra term added to the model e.g. Herman et al (7) in which (3.2.) is expanded to:

$$a_j(t+\tau) = \lambda v_r(t) + \varepsilon(t) \qquad (3.4.)$$

Here $\varepsilon(t)$ is a stochastic process, the so called "acceleration noise", which is present when the driver of a vehicle travelling along an empty road tries to maintain a constant speed. Measurements show that ε is approximately normally distributed, about a mean of 0 and with a standard deviation σ which is a function of the road (and vehicle and driver).

Values for σ found in practice (see Herman (7) and Montroll (8):

on a straight road with ideal surface	0.1 m/s^2
on a windy road with bad surface	0.6 m/s^2
in a tunnel with good surface	0.2 m/s^2

In most cases, therefore, it is possible to accomodate the above mentioned objections by extending the model. If all these extensions are required, however, the model threatens to become unmanageable.
As mentioned earlier, this research project is directed to the verification, at least in the beginning, of simple models. If these are found not to fit the real situation, the results will probably give some indications of the direction in which suitable extensions to the model may be found.

We shall now consider the last and most important objection, which is that in the models described up to now response is solely a function of the immediately preceding vehicle and not of any vehicles preceding this one, nor of any vehicles behind it. In theory this can be easily remedied, i.e.

$$a_j(t + \tau) = F_{-1}(\text{behaviour } j-1) + F_{-2}(\text{behaviour } j-2) + \dots\dots$$

$$+ F_1(\text{behaviour } j+1) + \dots\dots\dots \qquad (3.5.)$$

In practice, verifying this sort of model in real traffic is extremely problematical on account of the instrumentation. The only real solution seems to be offered by observation from the air, but as already pointed out, acceleration cannot be determined with a sufficient degree of accuracy using this technique.

III. VARIABLES TO BE MEASURED

In order to test car-following models, an instrumented vehicle (measuring vehicle) should be able to measure its own longitudinal motion and that of any following vehicle (follower). This means that the variables in the following list should either be measured directly or derived from other measurements:
a. acceleration of follower
b. relative speed of follower
c. vehicle separation
d. speed of follower
e. "on-off" state of measuring vehicle's brake light

Variable e has been included in the list due to its seeming relevance and its ease of measurement. These variables will hereafter be referred to as the car-following variables. There are also other factors which can influence the longitudinal motion of the follower and these can, to some extent, be determined by the crew of the measuring vehicle during the course of an experiment. Photographs taken of the follower can also be used for this purpose (see Chapter VI).

The following paragraphs summarize the so called non-specific car-following factors.

1. Type of measuring vehicle

This factor cannot be varied due to the measuring equipment requiring a specially adapted car. It is worth noting that the driver of the follower is probably unable to see through the measuring vehicle because of the measuring equipment.

2. Measuring vehicle's lateral position in its lane

This factor can be varied and its approximate value easily observed.

3. Follower's lateral position in its lane

It can probably be deduced from this factor whether the driver of the following vehicle is trying to see past the vehicle in front of it. This may be directly obvious to the observer in the measuring vehicle and/or it may be deduced from photographs taken of the follower.

4. Traffic situation in the vicinity of the measuring vehicle

The traffic situation comprises the composition (type of vehicle) and the driving style (speed, vehicle separation) of vehicles in front, beside and behind the measuring vehicle/follower combination in as much as it is relevant to the behaviour of the driver of the following vehicle. It is this last point, however, which is unknown. The ideal solution would be to observe the overall traffic situation from an aircraft accompanying the measuring vehicle. The high costs of such a procedure will probably restrict its use to a single occasion, so that another solution will have to be found for the great majority of measurements to be recorded by the measuring vehicle.

5. Characteristics of the driver of the following vehicle

The characteristics relevant to behaviour in traffic are, as yet, unknown, Moreover, only few characteristics can be observed in this situation, sex and age group being two fairly obvious ones. Such important characteristics as experience in traffic, especially on the road along which measurements are being carried out, and the mood of the driver cannot be observed.

6. Number and characteristics of passenger in the following vehicle

As far as the number is concerned, a classification into 0, 1, more than 1, seems sufficient. As for the characteristics, the most that will be observable is sex and age group.

7. Characteristics of the following vehicle

These characteristics can be based on the make of the vehicle and its year of manufacture (from the registration mark). Any faults in the car will, in general, not be visible.

8. Road characteristics

These characteristics might include: the number of lanes, width of the lanes, whether or not a hard shouldering present, type of road surface, condition of the road surface (e.g. wet), roadside structures, prohibitory and warning signs, gradients, bends, lighting. Except for lighting and the condition of the road surface, these characteristics are all permanent and can be recorded before or after the measurements.

9. Wheather

Precipitation, wind, fog and mist are important factors and can be easily observed.

10. Police surveillance

The visible presence of police surveillance during or before the measurements is of greater relevance than a general average presence. It is difficult, however, to determine what the driver of the following vehicle has seen before he is observed.

11. Special circumstances.

E.g. evidence of a recent accident, narrowing of the road due to road works.

Some remarks on this list:

1. This list is probably incomplete.
2. Some factors cannot be observed.
3. The number of factors that can be observed is rather on the large side, but, by suitable organisation of the measurements, it can be reduced.
4. There is no theory for the influence of these factors on the longitudinal motion of a vehicle.

If. however, a car-following model existed which could be reasonably well adapted to the longitudinal motion, it would mean that a number of parameters are given values such that the discrepancy between model and measurements is a minimum. A connection could then be sought between these parameters and the "other factors".

Furthermore, a research project could have as its aim (or one of its aims) the discovery of a connection between individual following-behaviour and overall traffic flow characteristics. This will require quantities such as traffic volume, speed distribution and percentage of lorries to be measured at fixed points along the road.

IV. ACCURACY REQUIREMENTS

The question arises as to how accurately the car-following variables should be known in order that the models can be tested and the parameters can be determined. In what follows an attempt is made to arrive at workable specifications. It has, however, been necessary to make rather many assumptions. This work has been based on the car-following models of type (3.1.) and of form (3.2.) and (3.3.). The left hand side of the equations represents the response of the follower. The requirement that a certain minimum response and a certain minimum response time must be observable leads to an accuracy requirement for the size of a_j and the time in which a_j changes. Requirements for the quantities on the right hand side of the equation follow from the requirements for the left hand side.

1. Accuracy of the acceleration of the follower

An important driver response is the driver taking his foot from the accelerator pedal, but not yet applying the brake. The resultant deceleration is approx. 1 m/s^2. It must be possible to clearly detect this deceleration, which, in terms of an accuracy requirement, is equivalent to a permissible error of the order of 0.1 m/s^2.

The acceleration of the follower is a continuous function of time. By the nature of the measuring system, this is converted into a variable which only assumes a value at discrete points in time. The choice of time interval Δt has a great influence on the measuring error. In any given measuring system a decrease in Δt will in general increase the measuring error.* The criterion for choosing a value for Δt is here based on the requirement that it should be possible to measure the response time of the "driver plus vehicle" system.

* The reason for this is that the acceleration cannot be directly measured, but is derived from the speed by differentiation.

Published research indicates that response times in car-following models such as (3.1.) vary from 0.4 to 2 seconds. For this reason Δt may not be given a value above 0.2 to 0.3 seconds.

Conclusion: permissible error in acceleration of the follower is of the order of 0.1 m/s^2, with a time interval of 0.2 to 0.3 sec.

2. Accuracy of the right hand side of the car-following equation

The error in determining the right hand side of a car-following model such as (3.1.) should be less than or equal to the error of the left hand side. While the form of the right side is not known, however, the effects of the errors in the various quantities cannot be determined. Using models (3.2.) and (3.3.), however, it is nevertheless possible to quantify the requirements to some extent.

3. Accuracy of the relative speed of the follower

Take equation (3.2.) as the model

$$a_j(t + \tau) = \lambda v_r(t)$$

Chandler et al's investigations (9) give a value for λ of approx. $\frac{1}{2}s^{-1}$.
Using this value, together with the requirement for a_j, immediately gives the requirement for v_r : permissible error is of the order of 0.2 m/s.

4. Accuracy of the vehicle separation

Take equation (3.3.) as the model.

$$a_j\ (t + \tau) = \mu v_r(t)\ \ x_r(t)^{-\alpha}\, v_j(t)^{\beta}$$

The error in a_j, δa_j, with respect to the error in x_r, δx_r, is then:

$$\delta a_j = \mu v_r(-\alpha)\ x_r^{-\alpha-1}\ v_j^{\beta}\, \delta x_r \qquad (5.1.)$$

The model defined by equation (3.3.) is a more sophisticated version of the model defined by equation (3.2.), λ being replaced by $\mu x_r^{-\alpha} v_j^{\beta}$.

Now assume that $\mu x_r^{-\alpha} v_j^{\beta}$ is also of the order of $\frac{1}{2}s^{-1}$. Then we have

$$\delta a_j = \tfrac{1}{2} v_r\ (-\alpha)\ x_r^{-1}\, \delta x_r \qquad (5.2.)$$

The permissible size of δx_r depends on the value of the parameter α and the combinations of v_r and x_r.

Take an unfavourable example:

Letting $\alpha = 2$ and $v_r = 20$ m/s, the requirement for δx_r is then $\delta x_r/x_r \leqslant \delta a_j/20$.

If $\delta a_j = 0.1$ m/s^2, the requirement becomes: $\delta x_r/x_r \leqslant 0.0005$. I.e. the permissible relative error in x_r is $\frac{1}{2}\%$.

5. Accuracy of the speed of the follower

Again take equation (3.3.) as the model.
The error in a_j resulting from the error v_j, δv_j is then:

$$\delta a_j = \mu v_r x_r^{-\alpha}\ \beta v_j^{\ \beta-1}\, \delta v_j \qquad (5.3.)$$

Again letting $\mu x_r^{-\alpha} v_j^{\beta} = \frac{1}{2}$ gives $\delta a_j = \frac{1}{2}\, v_r^{\beta}\ \ v_j^{-1}\, \delta v_j$.

Let $\beta = 1$ and $v_r = 20$ m/s. The requirement for δv_j is then:

$\delta v_j / v_j \leqslant a_j / 20$.

If $\delta a_j = 0.1$ m/s^2, the permissible relative error in v_j is 1%.

Note 1: The above quantitative requirements are very provisional. The real requirements will probably only become apparent after experimentation has begun.

Note 2: The requirements apply to the variables themselves. If the variables are not directly measured, but instead are derived from other variables, the requirements for these other variables follow from the requirements for the first set of variables.

Note 3: It is worth considering the permissible error in the acceleration of the follower, of the order of 0.1 m/s^2, in the light of the naturally occuring "acceleration noise" mentioned in chapter II and having standard deviations of 0.1 to 0.6 m/s^2. It might be concluded from this that the requirement is too strict and that there is the risk insisting on measuring the irrelevant noise component of the acceleration.
On the other hand, it seems (see for example Herman (7) and Torres (10)) that accelerations in car-following situations in normal traffic do not usually fall outside the range -1.5 to +1.5 m/s^2. This shows that measuring and interpreting the acceleration of a vehicle is rendered extremely difficult by the signal and noise level being similar in magnitude.

V. MEASURING TECHNIQUES

The variables describing the motion of the randomly selected follower caused considerable difficulty. From the measuring vehicle it is only possible to determine the relative motion of the following vehicle. The absolute motion of the follower is then obtained by taking into account the motion of the measuring vehicle.

There are several solutions:

A. Measure x_r and v_{j-1}.
Differentiate x_r to obtain v_r.
v_j is derived from v_r and v_{j-1}.
a_j is obtained by differentiating v_j.

B. Measure v_r and v_{j-1}.
v_j and a_j are then obtained as in A.
x_r is obtained by integration of v_r; a constant of integration being needed for this, i.e. the value of x_r at a given time. In practice, x_r will be determined more often in order to calibrate the integration.
Measuring v_{j-1} does not seem to pose an insurmountable problem and so it will not be considered in any great detail.

The following measuring techniques have been short-listed for measuring x_r or v_r.

1. Photographic techniques

Photographs are taken of the follower and the distance x_r is derived from the apparent increase or decrease in size of a fixed and known dimension on the front of the following vehicle. It seems that although this method is suitable for determining x_r with sufficient accuracy, its precision is inadequate for v_r and a_j to be derived with the required degree of accuracy.

2. Acoustical techniques

Distances and speeds can also be measured with sound waves, modulated or unmodulated. These techniques do not seem as suitable due to the speed of sound in air being rather dependent on air temperature and humidity.

3. Optical techniques

The recently discovered possibilities of laser beams seem particularly promising.

In October 1969, the Institute for Applied Physics TNO - Delft University of Technology (T.P.D. T.N.O.-TH) was given the task of examining whether lasers can be used for measuring vehicle separations, the specifications given being: separation distances 5-50 m; precision: a few cms; interval between measurements: 2 to 5 sec.

In the T.P.D. T.N.O.-TH report of December 1970, a certain measuring system was proposed which meets the specified requirements. Further research into the elements of this system was considered necessary.

The reason for not continuing this project is that the proposed system requires the laser beam to remain aimed at the registration plate of the following vehicle. The only way of solving this attendant problem would seem to be by means of expensive servo-systems.

4. Radar techniques

The use of pulse radar for measuring x, is unsuitable as the short duration of the pulse leads to considerable technical problems.

Measuring v_r by continuous wave radar, i.e. Doppler radar, seems a suitable method.

In addition to these, there are more sophisticated radar techniques e.g. those employing frequency modulation of the carrier signal. These will only be considered if Doppler radar proves to be unsuitable.

During the course of the preliminary survey of possible measuring

techniques, information was obtained, not only from published literature, but also through personal contacts in industry and scientific establishments.
Information from all these sources led to the conclusion that Doppler radar offered the greatest chance of success.

VI. THE SELECTED MEASURING TECHNIQUE

Measurements are carried out as described in solution B in Chapter V. Relative speed v_r is determined by means of Doppler radar. Based on the requirement for the acceleration of the follower a_j, the requirement for v_r becomes: permissible error of the order of 0.01 m/s with $\Delta t = 0.2$ to 0.3 sec.
The speed of the measuring vehicle v_{j-1} is determined by means of a not yet fully specified instrument. Using the requirement for a_j, we obtain: permissible error: as for v_r.
Vehicle separation x_r is obtained by integration of v_r. The constant of integration is determined from a measurement of x_r using the photographic technique, possibly more than once per successive measurement of $v_r(t)$.
Photography is also used for determining a member of non-specific car-following factors.

The Doppler radar apparatus is the most critical element of the selected measuring method and the remaining pages will therefore be mainly devoted to this subject.

VII. DOPPLER SPECIFICATIONS

These specifications are only appoximate, it being impossible to determine in advance exactly what requirements must be met and under which circumstances.

1. Range of measurements

In general the relative speed will be fairly small. The range is provisionally put at -10 to + 20 m/s, i.e. the follower approaches with maximum v_r of 20 m/s and separates with a maximum v_r of 10 m/s. (A smaller range is sufficient for investigations solely into following-behaviour).

2. Accuracy

The permissible absolute error in v_r is of the order of 0.01 m/s with a measuring interval Δt of 0.2 to 0.3 sec.
We are here concerned with the absolute error, as v_r must still be differentiated.

3. Range of operating distances

Relative speeds should be measurable at separations of 1 m to 50 m, and preferably up to 100 m between the measuring vehicle and the follower.

4. Traffic environment

Measurements should be able to be made on all lanes of motorways and trunk roads in conditions of high volume traffic.

5. Camouflage

During the "in traffic" measurements the driver of the following vehicle must not notice that he is being observed. This factor is reflected in the dimensions and disposition of the apparatus, especially in the case of the aerial.

6. Installation for operation in a moving vehicle

Such operating conditions make demands on the ruggedness of the apparatus and restrict the available sources of power.

7. Output quantities (Transmitted radiation)

The best choice of output quantity would seem to be the low frequency Doppler signal, the frequency of which is proportional to the absolute relative speed, and the sign (plus or minus) of the relative speed. These should be suitable for either analogue of digital recording.

VIII. INTERFERING FACTORS

Under ideal conditions a Doppler radar installation can satisfy the specifications drawn up in respect of: range of measurements, range of operating distances, and accuracy. Ideal conditions in this situation mean a rigidly mounted aerial receiving signals from a flat surface. The real situation is very different. Several interfering factors which detract from the ideal functioning of the radar installation will now be discussed.

1. The following-vehicle is a rather fussy shaped reflecting object. This results in a complex reflected signal which may exhibit phase shifts and may even be extinguished by damping. Little can be done to remedy such effects. A possible solution for entire signal loss is to install a second receiving aerial. Switching from one aerial to the other must be done automatically, dependently of the strength of the incoming signal.
It is quite possible that "round-nosed" cars (VW Beetle, 2 CV) are such bad reflectors that their speed cannot be measured. This would mean that the measuring technique is unsatisfactory.

2. In addition to longitudinal motion, which is the object of the study, the follower also displays other sorts of motion due to irregularities in the road surface, accelerating away, braking, taking bends, and engine vibrations.
Movements arising from irregularities in the road will probably have a frequency higher than that of the longitudinal variations in speed with which we are here concerned, although this will vary considerably according to the type of car. Lateral speed will, in principle, not be registered by the Doppler radar, but they may well modify the reflection pattern.

3. The vehicle is which the Doppler radar is installed is also subject to interfering motion from the road surface, braking, etc. As a consequence, the transmitted signal has no fixed direction. This extraneous movement can be reduced by mounting the aerial on a platform kept level by a servo-system. This

solution is unattractive, however, on account of the high cost of its realization.

4. Reflections from the road surface. Reflections from the road which go straight back to the aerial (retroflections) give rise to a speed registration in the neighbourhood of the measuring vehicle's speed. As a result it may be possible to remove this spurious effect by filtering. Elimination by suitable choice of aerial dimensions would, however, be preferable.
The road surface can also act as a mirror and thereby allow multiple path effects which can cause interference.
It is also conceivable that dry and wet roads may produce differing interferences.

5. Reflections from roadside objects e.g. crash barriers, bridge parapets, lamp posts, traffic signs, trees.
In general, the same applies here as for the road surface.

6. Reflections from other traffic. These can be classified into:
a. other following vehicles. These will be partly in the "shadow" of the directly following vehicle and furthermore will be at a greater distance, which may mean that this factor is not so important;
b. adjacent vehicles (cars in other lanes which overtake or are overtaken by the measuring vehicle and follower). These are probably the greatest source of interference as the may remain in the vicinity for a considerable length of time and, moreover, the relative speeds of the follower and of the adjacent vehicle are fairly similar;
c. oncoming vehicles. Individual oncoming vehicles are only present for a short tine and have a high relative speed which enables filtering to be employed. The numbers of oncoming vehicles may be so high that this interference is present practically the whole time.
7. Bends and gradients in the road. These can cause the beam to point above, below, or to one side of the following-vehicle.

The only remedy would seem to be aiming the aerial by hand.

8. Weather conditions such as rain, fog and mist. Radar operating at wavelenghts of 2 to 3 cm seems unaffected by rain of fog, but 9 mm radar will probably experience interference from rain due to scattering.

9. Special circumstances, e.g. underpasses, tunnels and power lines above the road. It seems acceptable not to carry out measurements in such circumstances if it turns out that they cause difficulties.

IX. CONCLUSIONS

After considering the specifications and the interfering factors present, radar specialists who where consulted on the problem concluded that advanced equipment, not yet developed would be required for such a measuring programme. Development of this apparatus would be a costly, long-term project whose success could not be guaranteed in advance. On the grounds that development of measuring apparatus does not fall within SWOV's specific range of activities, it was decided not to take on the task.

Research into following-behaviour, as sketched out in this report, is consequently not feasible. Neither is it possible to conduct research into car-following models by means of aerial photography or sensors on the road.

The consequence for the overall programme of traffic flow research is that for the time being investigations will have to make do with recording and analysing less detailed data than the acceleration and deceleration of individual vehicles.

LITERATURE

1. Fox, P. & Lehman F.G. Safety in car following; A computer simulation. Newark College of Engineering, 1967.

2. Wallner, F. Zum Einfluss konstruktiver Massnahmen am Fahrzeug auf das Folgeverhalten einzelner Fahrzeuge und auf das dynamische Verhalten von Fahrzeugkolonnen. Strassenverkehrstechnik 6 (1969) 177 - 184.

3. Rockwell, T.H.; Ernst, R.L. & Hanken, A. A sensitivity analysis of empirically derived car-following models. Transportation Research 2 (1968) 363-373.

4. Ohio State University. Investigation of traffic dynamics by aerial photogrammetry techniques. Interim-rapport EES 278-3. Ohio State University, 1970.

5. Breiman, L. On estimating position and velocity of cars from discrete time aerial photographic data. System Development Corp, 1969.

6. Lewis, P.A. Driver behaviour equations: Some limits on their solution due to vehicle dynamics. Traffic Engineering & Control 12 (1970) 414 - 416.

7. Herman, R. et al. Traffic dynamics: Analysis of stability in car-following. Operations Research 7 (1959) 86 - 106.

8. Montroll, E.W. Acceleration noise and clustering tendency of vehicular traffic. Proceedings Symposium theory traffic flow I/1959/147-157.

9. Chandler, R.E.; Herman, R.; Montroll, E.W. Traffic dynamics: Studies in car-following. Operations Research 6 (1958) 165-184.

10. Torres, J.F. Acceleration noise, power spectra and other statistics derived from instrumented vehicle measurement under freeway driving conditions. System Development Corp, 1969.