Multilane Traffic Flow Process: Evaluation of Queuing and Lane-Changing Patterns

Jens Rørbech, Laboratory of Road Data Processing, Road Department, Denmark Ministry of Public Works

This paper presents a queue-theoretical model for describing traffic flow on a dual two-lane motorway. The model is based on the theory of stationary Markov processes and is closely related to data collection methods made possible by specially developed recording equipment. The model is based on a description of the driver's behavior in traffic. The individual driver alternates between driving under free-flow conditions (state F) at his or her desired speed and without delay and driving in a queue (state K) with consequent delay. To escape from or possibly entirely avoid a queue, a driver must change lanes (alternate between lane 1 and lane 2). The behavior of the driver is thus described by a variable that assumes the discrete values 1F, 1K, 2F, and 2K. This process can be described as a Markov process. The reactions of individual drivers are summed up in a comprehensive description of the average driver's behavior, so that the road traffic model developed is an example of a macrostochastic model. A technique has been developed by which the parameters in the Markov process can be estimated from the collected data, and the paper describes how the model becomes part of a detailed investigation into the vital conditions affecting motorway traffic, e.g., capacity, relationship between speed and traffic volume, and the drivers' use of the motorway.

This paper presents a method for describing the traffic flow on a four-lane motorway and for quantitatively evaluating factors that have a bearing on the traffic flow. A more comprehensive description of the work on the traffic model has been published elsewhere (1). Traffic flow is described as a stationary Markov process.

Breiman (2) discussed some of the road traffic models prepared so far: microscopic, macroscopic, and stochastic models. Microscopic and macroscopic models are deterministic; i.e., they usually compare the traffic with mechanical and physical processes and are in fact unsuitable for describing the traffic situations that are of interest in practice. This is because the traffic situation on a motorway under normal conditions is a result of the correlation among a great number of more or less casual conditions that cannot so easily be represented by means of mechanical or physical analogies.

Stochastic models, however, are of assistance in the construction of traffic engineering models. It is, after all, an intrinsic feature of any traffic flow that it must, through a limited application of service resources, meet manifold demands of individual units with respect to service time, method, speed, and the like—conditions that can often be fairly well described by means of relatively simple stochastic processes. In particular, the theory of queues is, after all, concentrated on the construction of models for queue systems where basic conditions such as the probability of rejection or delay, the number of units in the queue, and the average delay can be calculated provided that the queue system can be broken down into clearly specified functions. The first works concerned with the theory of queues were in fact undertaken to solve purely practical problems in connection with the dimensions to be adopted for telephone installations.

Despite this apparently obvious aid, there are few road traffic models based on stochastic processes, and, with few exceptions, discussion has been confined to descriptions of partial problems in traffic flow. One of the reasons is that road traffic cannot so easily, e.g., as telephone traffic, be subordinated to the specified functions of the conventional theory of queues. For instance, it can rarely be assumed that the arrivals of cars are governed by the Poisson distribution, i.e., that they are independent of each other; as a rule, queues can be observed even when traffic volumes are light, so that all the problems associated with overtaking come into play.

The present road traffic model is therefore based on a description of drivers' behavior in traffic.

THE MODEL

The following description of motorists' behavior on a motorway can be used purely logically to classify a series of conditions affecting the traffic flow process and as a model-technical basis for a data collection technique. It is assumed that all motorists can be divided into two types representing extremes in driving behavior.

The first type is drivers who keep to the right as much as possible. As long as there is room in the right lane, they travel there at the desired speed. If they catch up with a slower driver, they overtake him or her if there is room in the left lane; otherwise, they wait in the queue. As soon as they have completed an overtaking maneuver,

Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service and Committee on Traffic Flow Theory and Characteristics.

they return to the right lane again.

The second type is those drivers who have only one thing in mind: fast driving in the left lane. They force their way by flashing their lights and sounding their horns. Occasionally, they get into a queue, but they stay there only until they have forced the driver in front of them to move to the right. They themselves may also be forced to the right if an even faster driver of their own kind appears in the rear-view mirror; that is what they really respect.

Drivers in both groups alternate between traveling under free conditions at the desired speed and without loss of time (state F) and traveling under queue conditions with loss of time (state K). They have to change lanes (alternation between traveling in lane 1 and traveling in lane 2) to escape from or possibly completely avoid a queue. In other words, the behavior of the motorists on the road is described by a variable that may adopt the discrete values 1F, 1K, 2F, and 2K. This process may reasonably be described as a stationary Markov process.

Figure 1 shows the alternation of the motorists between the four states 1F, 1K, 2F, and 2K. It appears that both models of driving described above (both those who keep to the right and those who keep to the left) lead to the same pattern of change between the four states because of the way in which the queues are formed and dissolved.

The parameters in the Markov process that are registered during the recordings are partly the probability of remaining in the four states and partly the transition probabilities between the different states. The data collection technique and the estimation of the parameters in the Markov process are described below.

THE RECORDINGS

The values of the parameters in the road traffic model were determined with the aid of the recording arrangement shown in Figure 2. One carriageway of the motorway was fitted with eight detectors (tape switches) so that each car was recorded twice. The passage times of all automobiles were recorded separately on a digital magnetic tape recorder. A description of this very special equipment is given elsewhere (1, appendix).

Among the data recorded at each passage were vehicle, position, arrival time, speed, and wheelbase and the queue situation (i.e., whether the car was in a free-flow situation or in a queue situation). Computer programs were used to analyze the recorded passage times. The question of defining the condition of driving in a queue is dealt with elsewhere (1, appendix).

For each passage, the following data are therefore recorded twice (i.e., at cross section A and again at cross section B):

1. Position in the carriageway, lane 1, lane 2, lane change from 2 to 1, and lane change from 1 to 2; and
2. Queue situation, free flow or queue.

With the determination of the wheelbase, the different cars can again be identified at cross section B (the degree of uncertainty with which the wheelbase is determined is much less than the natural spread of wheelbase sizes). In other words, it is possible to record not only the distribution of the cars over the four state variants but also the rate at which they change from one state to another.

An example of the alternation of 800 cars between the different states is shown below, corresponding to the midday traffic in Table 1 described later. The traffic volume is 1081 cars/h and the distance L between cross sections A and B is 100 m (328 ft).

State	1F	1K	2F	2K	Total
1F	244	20	7	2	273
1K	17	50	2	2	71
2F	15	1	294	23	333
2K	1	0	14	108	123
Total	277	71	317	135	800

The Markov property has been tested by recording the traffic at three cross sections A, B, and C and by determining whether a stochastic independence can be assumed between the observations at cross sections A and C while the value at cross section B remains constant. The stationary character has been similarly tested by comparing the observed distributions of the states of the cars at the three cross sections.

Three different traffic volumes are considered in these tests: a situation of light traffic, called morning traffic; a situation of medium-heavy traffic, called midday traffic; and a situation of heavy traffic, called evening traffic. In all three situations, it can reasonably be assumed that the behavior of the drivers on the road can be described by the stationary Markov process shown in Figure 1.

Because of the stationary character of the Markov process, the observations can be confined to a single cross section and can then be generalized to apply to a road section of theoretically indefinite length.

ESTIMATING PARAMETERS IN THE MARKOV MODEL

The recording method described above yields, as a result of the observations, a transition matrix that indicates the states of the individual drivers at the two extreme cross sections of the recording section.

The parameters that determine the actual Markov process are the state probabilities P'_i and the transition intensities Q''_{ij} where P'_i indicates the probability of a car being in state i at a given moment and $Q''_{ij}\,dl$ $(i \neq j)$ indicates the probability of a transition from i to j over the short distance dl. The transition probabilities $P''_{ij}(L)$ are of interest. $P''_{ij}(L)$ is the probability of a transition from i to j over the distance L.

Between the parameters there are the following relations

$$P' = P' P''_{ij} \qquad \sum_i P'_i = 1 \tag{1}$$

from which the state probability P' can be found when the transition probability P''_{ij} is known. In the same way the state probability P' can also be found from

$$P' Q'' = O' \qquad \sum_i P'_i = 1 \tag{2}$$

when Q'' is known.

Between the transition intensities and the transition probabilities, the following correlation exists:

$$P'' = \exp(Q'' L) \tag{3}$$

Equations 1, 2, and 3 are valid provided that statistical equilibrium has occurred.

In the estimation of the parameters of the Markov model on the basis of the observations, two considerations in particular become decisive.

1. The sums of lines and columns in the observation matrix will hardly be identical as is demanded if sta-

Table 1. Results of observations on Elsinore Road, 1969.

Traffic	Volume (cars/h)	1F	1K	2F	2K	Number of Lane Changes
Morning	524	30 400 m, ~33.0 stretches of 920 m	1100 m, ~7.4 stretches of 154 m	59 000 m, ~45.2 stretches of 1305 m	9500 m, ~21.3 stretches of 448 m	51.1
Midday	1081	33 500 m, ~50.9 stretches of 658 m	8700 m, ~31.9 stretches of 273 m	41 200 m, ~48.4 stretches of 853 m	16 600 m, ~30.4 stretches of 545 m	37.9
Evening	2736	20 300 m, ~101.9 stretches of 199 m	39 000 m, ~93.7 stretches of 416 m	15 400 m, ~48.2 stretches of 318 m	25 300 m, ~41.3 stretches of 612 m	16.4

Note: 1 m = 3.28 ft; 1 km = 0.62 mile.

Figure 1. The alternation of the motorists between the four states.

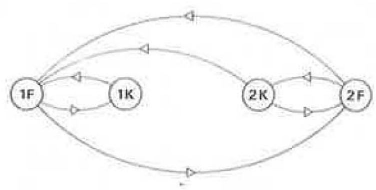


Figure 2. Recording arrangement for determining the values of the parameters in the road traffic mode.

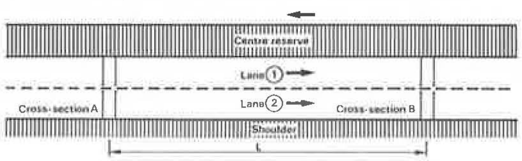


Figure 3. Distribution of drivers over the four state possibilities as a function of the traffic volume and the level-of-service specifications given in the Highway Capacity Manual.

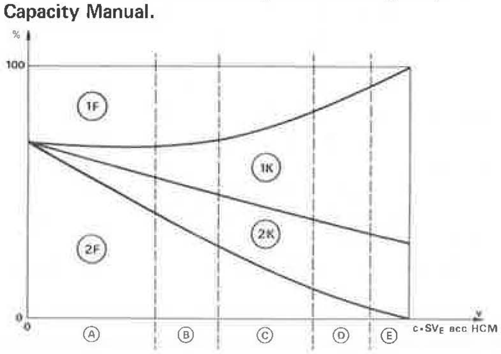
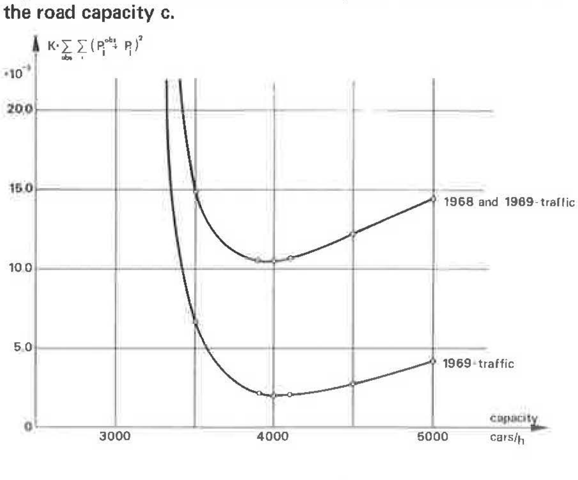


Figure 4. The minimized sum of the squares K as a function of the road capacity c.



tistical equilibrium is assumed.

2. The recording method described earlier merely indicates the states of the individual cars at the extreme points of the recording section whereas the continuous Markov model permits a theoretically infinite number of transitions between the recording points; i.e., the recording method aims more directly at determining the transition probabilities P''_{ij} than the transition intensities Q''_{ij}.

In connection with the work on the road traffic model, an estimation technique has therefore been worked out in which these problems are taken into consideration. The estimates are carried out in a series of stages (1).

1. The transition probabilities that meet the demand for statistical equilibrium are estimated on the basis of a maximum likelihood assumption. This P_{ij} matrix meets the requirement of identical sums of lines and columns (statistical equilibrium has been reached) and forms the basis for the calculation of a set of state probabilities and a set of transition intensities. The latter do not, however, meet the requirement of the transition diagram inasmuch as five of the transitions are not permissible (Figure 1).

2. While the state probabilities generated in stage 1 above are kept constant, the prohibited transitions (defined as the transition intensities generated in stage 1) are shifted in the transition diagram in such a way that the transitions now follow permissible sequences. For instance, the prohibited transition 1K → 2K is now shifted to 1K → 1F → 2F → 2K. Because the process is, after all, a continuous Markov process, it is quite permissible to assume that a motorist changes his or her state repeatedly over the observation section. This gives rise to a new set of transition intensities and therefore also to a new set of transition probabilities. The state probabilities from stage 1 remain unchanged and are kept constant during the entire phase.

3. The estimated parameter values determine a new transition matrix, and a good check is obtained by comparing the observed and the estimated transition matrices. An observation matrix has been represented. The corresponding matrix generated from the estimated parameter values is

State	1F	1K	2F	2K	Total
1F	234.0	19.9	13.4	0.5	267.8
1K	19.9	49.3	0.6	0.0	69.8
2F	12.7	0.6	295.6	21.0	329.9
2K	1.2	0.0	20.3	111.0	132.5
Total	267.8	69.8	329.9	132.5	800.0

The estimated parameters describe a traffic situation inasmuch as the state probabilities determine the average total distance traveled in the individual states, whereas the transition intensities determine the length of time during which the drivers remain in the specific states.

Table 1 gives a summary of the results from recordings during situations of light, medium-heavy, and heavy traffic volumes. The recordings date back to 1969 when there were no general speed limits in Denmark and come from an old motorway, Elsinore Road, north of Copenhagen. The tabulations indicate the average conditions encountered by the motorists. During morning traffic, for example, motorists will on the average cover 30 percent of the distance in state 1F, 1 percent of the distance in state 1K, 59 percent in state 2F, and 10 percent in state 2K. A motorist traveling freely in lane 1 will, on the average, be able to travel about 900 m before changing to another state.

CONCEPTS OF CAPACITY AND LEVEL OF SERVICE

Apart from this general description of the traffic situations on Elsinore Road, the road traffic model has been used for discussing in greater detail various vital conditions. The concepts of capacity and level of service and the correlation between speed and traffic volume are discussed below.

If the driver classification in the suggested road traffic model is applied to the approach chosen in the Highway Capacity Manual (3), namely, that the traffic flow on an open section of road for $0 < v/c < 1.0$ will take place at levels of service ranging from A to E, the distribution of the drivers over the four state variants can be illustrated as shown in Figure 3.

It is particularly important to determine the boundary conditions. If the different state probabilities are called P_i (i = 1F, 1K, 2F, and 2K), one arrives at the following results: If the volume-capacity ratio is approximately equal to zero, i.e., level of service A, queue conditions will hardly occur except over short distances; i.e.,

$$P_{1F} + P_{2F} \simeq 1.0 \qquad P_{1K} \simeq P_{2K} \simeq 0 \tag{4}$$

The distribution of the drivers over the two lanes will be governed by, among other things, driving habits, the distribution over the driving models mentioned earlier, and the distribution of the desired speeds. If $v/c \sim 1.0$, i.e., level of service E, all the cars will travel under queue conditions. There will hardly be any lane changing, for it is not possible to escape, in this way, from the queue situation:

$$P_{1F} \simeq P_{2F} \simeq 0.0 \qquad P_{1K} + P_{2K} \simeq 1.0 \tag{5}$$

In this situation, too, the distribution of the drivers over the two lanes will be governed by driving habits. A decisive factor will be the way in which the entire saturation process takes place, again depending on, among other things, the distribution over the driving models, the distribution of the desired speeds, and the risks that the drivers are willing to take to approach their desired speeds as closely as possible.

An estimate of the positions of the boundary lines shown in Figure 3 for the four state variants has been made on the basis of the observations on the Elsinore Road by means of a regression analysis; the structure is apparent from Figure 3. Broadly speaking the drivers use the motorway in one way during light traffic when the right lane (lane 2) handles the greater part of the traffic volume and in another way during heavy traffic when the left lane (lane 1) handles the greater part of the traffic volume. An evaluation of this use of the motorway is given later; it is shown that the distribution is connected with the queue formation pattern and consequently the transition diagram shown in Figure 1.

Fixing of the lines in Figure 3 implies, as the problem is formulated, that the capacity of the road is known beforehand. The regression analyses have been carried out with capacity ranging from 3000 to 5000 cars/h (for two lanes in one direction). In other words, the capacity of the road, c, has been included as a variable in the calculations, which permits an estimate of this vital quantity.

Figure 4 shows the minimized sum K of the squares as a function of the variable capacity c for two series of observations. The best possible agreement between the model and the observed data is obtained when c = 4000 cars/h (for two lanes in one direction), which is the value the Highway Capacity Manual recommends for a motorway like the Elsinore Road.

SPEED-VOLUME RELATIONSHIP

The speed-volume relationship is determined in three stages. All these are time-mean speed relations because of the way in which the observations are arranged. The state probabilities are, after all, measured at one cross section, which means that P_i are time probabilities [the concepts of space-mean speed and time-mean speed as related to the present road traffic model are discussed in greater detail elsewhere (1).]

First, the distribution of the drivers' free speeds is estimated. Thus the mean speed V_f is determined, which represents the left end of the speed-volume curve and the point of intersection with the $v/c = 0$ axis.

The frequency distribution of the free speeds is shown in Figure 5. The speed distribution has been determined as follows: Observations were made during a 2½-h period at a time when the traffic flow on the Elsinore Road was particularly light; 250 cars in lane 1 and 250 cars in lane 2 were selected that traveled at distances greater than 300 m (1000 ft) behind the car in front. The speed distributions corresponding to the two lanes were determined separately and then added up to show, on the basis of the average distribution over the two lanes, the total frequency distribution of the speeds.

In practice it is hardly possible to determine a distribution function of the free speeds on any very reliable basis inasmuch as the selection of the cars traveling under free-flow conditions will always be subject to uncertainty. It is, for example, rather likely that cars of a certain high-speed class will be the first to be caught in a queue and will therefore not frequently be represented as driving under free-flow conditions.

Figure 4 shows the best estimate of the motorists' desired speeds, which have been checked in various ways. It is, for instance, apparent from Figure 5 that there is a logically correct correlation between the desired and observed speeds in the three traffic situations. It can also be shown that those motorists who, in the three traffic situations, travel under free-flow conditions can be isolated as components of that group of drivers that are determined by the distribution of the free speeds.

In the second stage, the speed conditions of the drivers in the capacity situation are evaluated and the mean speed V_m is determined, which represents the right end of the speed-volume curve and the point of intersection with $v/c = 1.0$.

The speed in the capacity situation is determined on the basis of observations of cars traveling under queue conditions in the two lanes. Figure 6 shows the observed time intervals for cars traveling under queue conditions, plotted in the form of speed-volume functions.

As with the free speeds, V_m cannot be determined unequivocally, but a reasonable estimate of V_m can be made on the basis of the observations shown in Figure 6.

Because driving speed in the capacity situation could not be accurately estimated, the final determination of

Figure 5. Distribution of free speeds and those based on observations on the Elsinore Road.

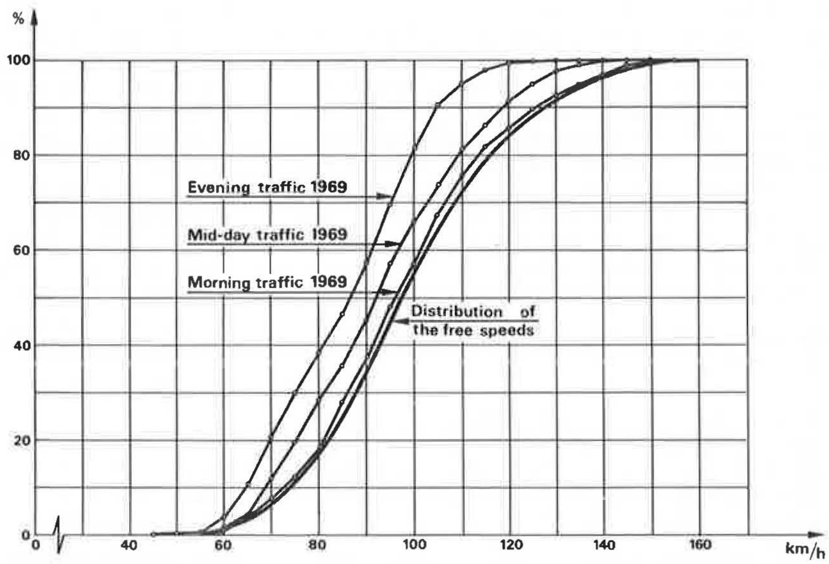
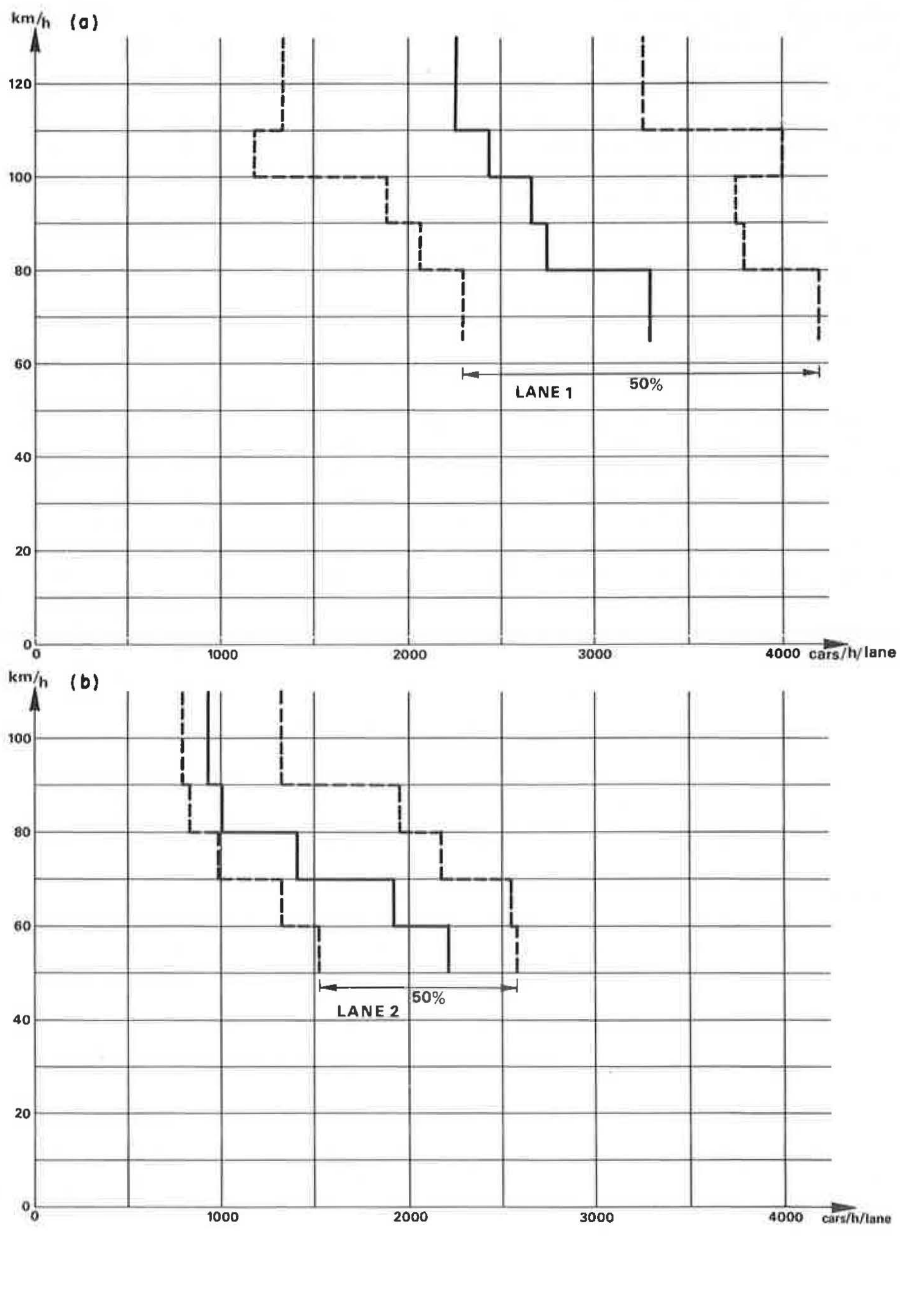


Figure 6. Observed time intervals for cars traveling under queue conditions in (a) lane 1 and (b) lane 2.



the speed-volume curve allows for three alternative values of V_n as shown in Figure 7. The three values were based on the observations of queue conditions in the two lanes (speed distributions for 1K and 2K, Figure 6) and on alternative assumptions concerning the degree to which the drivers will, in the capacity situation, adopt a rational distribution over the two lanes in accordance with their desired speeds, i.e., with high-speed drivers preferring lane 1 and low-speed drivers lane 2.

In the third stage, the shape of the curve in the interval $0 < v/c < 1.0$ is determined. This is done by estimating, on the basis of the recorded probabilities P_i (i = 1F, 1K, 2F, 2K) and the probabilities of transitions between these states, the probability of the drivers being caught in a queue in the two lanes. The result of the estimate is shown in Figure 7.

The shape of the curve in the interval $0 < v/c < 1.0$ is determined by considering the conditions for an average driver who wants to travel at a speed equal to the mean speed of the drivers' desired speeds V_f. As long as the average driver is traveling in the 1F or 2F state, the speed is V_f and no time is lost. In situations 1K and 2K, the driver is traveling at a speed lower than V_f and therefore loses time.

The time-mean speed as calculated on the basis of the behavior of the average driver then becomes

$$V_T = P_{1F} V_f + P_{1K} V'_{1K} + P_{2F} V_f + P_{2K} V'_{2K} \qquad (6)$$

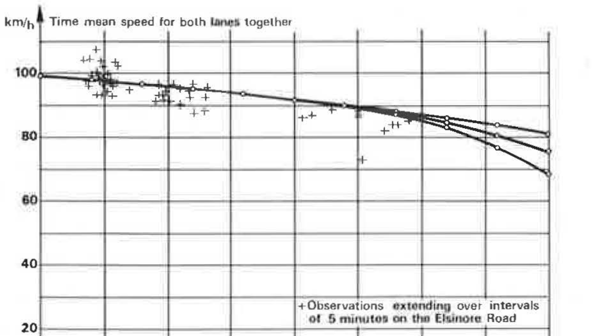
where V'_{1K} and V'_{2K} = speed of the average driver in the two queue situations.

Rørbech (1) describes how the speed in the two queue situations as a function of the traffic volume is estimated from the probability of a driver traveling at free speed being caught in a queue, i.e., on the basis of the observed transition intensities q_{FK}. During light traffic the transition intensities q_{FK} are small inasmuch as the risk of being caught in a queue is low. During the whole saturation process the probability of traveling under queue conditions is increased as $q_{FK} \rightarrow \infty$, when $v/c \rightarrow 1.0$.

The speed-volume relationship shown in Figure 7 has the form of a steadily decreasing function. The alternative values for the speed in the capacity situation merely affect the last part of the speed curve. Figure 7 shows a number of 5-min observations, which cover a much longer observation period than those that determine the parameters in the Markov process. That is, the data that determine the speed-volume relationship are in principle independent of the plotted speed observations.

The computed curve for the range beyond the very low traffic volumes lies at the upper edge of the observed speeds, but the difference hardly exceeds 5 km/h (3.1 mph) on average.

Figure 7. Speed as a function of the traffic volume.



DRIVERS' USE OF THE MOTORWAY

The transition diagram of Figure 1 can be plotted identically for both of the two ways of driving mentioned earlier (i.e., both the motorists who keep to the right and those who keep to the left) because both ways of driving lead to the same queue formation pattern. A strictly logical consequence of the two behavioral models will therefore take the form of the following queue formation patterns in the two lanes. In the slow lane, an inequitable queue formation will take place in which the driver who arrives first in the queue is the one who will be served last. All the traffic gaps in the left lane will be snatched by the later arrivals in the queue. In the fast lane, an equitable queue formation will occur in which the driver who arrives first in the queue will also be the one who gets out of it first when the slow car in front moves to the right lane.

The difference in queue formation patterns in the two lanes has a decisive influence on the whole use of the road. In light traffic most motorists travel in the right lane. Only about one-quarter of them travel at high speed in the left lane, and they can easily make their way. On the other hand, many drivers, even in light traffic, will travel under queue conditions in the right lane. The reason is that, if they try to make an overtaking maneuver, it will not be long before a fast driver will urge them into the right lane again by flashing his lights; in fact, the road is not used very efficiently in light traffic conditions. At any rate this was the case before the speed restrictions were introduced in Denmark.

In heavy traffic the pattern becomes different. Those who want to drive fast find it more difficult to proceed, and the many drivers who want to travel at medium speeds (i.e., 80 to 100 km/h or 50 to 60 mph) take this opportunity, possibly too eagerly, to move out into the left lane. In heavy traffic almost three-quarters of the motorists travel in the left lane, obviously because of the higher traveling speed. The queue pattern in the right lane is a strong incentive: If one is caught in a queue here, it is almost impossible to get out of it again. Because of the inequitable queue formation pattern, those

Table 2. Effect of a speed restriction on the traffic flow process.

		110-km/h Limit		120-km/h Limit		130-km/h Limit		140-km/h Limit	
Condition	Observed Mean Speed (km/h)	New Mean Speed (km/h)	Cars Disturbed (%)	New Mean Speed (km/h)	Cars Disturbed (%)	New Mean Speed (km/h)	Cars Disturbed (%)	New Mean Speed (km/h)	Cars Disturbed (%)
Motorists' desired speed	99.4	95.3	28	97.4	16	98.6	8	99.2	3
Morning traffic	97.9	94.1	25	96.0	14	97.1	8	97.7	3
Midday traffic	92.9	90.8	19	92.2	9	92.7	3	92.9	0
Evening traffic	85.6	85.3	5	85.5	0	85.5	0	85.6	0

Note: 1 km/h = 0.62 mph.

cars that join the queue later, i.e., those that travel behind, will snatch all the gaps in the fast lane. This is because the gaps in the fast lane are first available to the cars in the rear of the slow-lane queue.

In themselves these statements are very obvious but, in fact, it has never before been realized that the result was such an uneven, and consequently varying, distribution of the traffic in the two lanes, i.e., most drivers in the right lane during light traffic and most drivers in the left lane during heavy traffic.

One cannot help wondering whether this is an appropriate way of driving. Is the motorway as a technical installation utilized to a sufficient degree? A detailed analysis shows that, in heavy traffic, the uneven distribution leads to a very nearly optimal utilization of the road. It is, in fact, worthwhile for as many as 75 percent of the drivers trying to travel in the fast lane at speeds ranging from 70 to 80 km/h (45 to 50 mph).

It has already been mentioned that, in light traffic, the uneven distribution of the drivers over the two lanes does not represent proper use of the road. The few drivers wanting to travel fast may be able to dominate too much. In this respect, the speed limits recently introduced in Denmark on an experimental basis may have an important bearing. Apart from their generally beneficial influence, these speed limits are also likely to result in an increase in mean speed. This is studied in greater detail below.

Table 2 gives the recorded mean speeds corresponding to the three different situations on the Elsinore Road from Table 1, supplemented by an estimate of the average speed at which the motorists would have wanted to travel if there had been no disturbances from other motorists. As mentioned, all four situations are related to a situation without speed limits.

The table also gives the mean speeds that would result if all the drivers, either voluntarily or under compulsion, obeyed an upper speed limit of 110, 120, 130, or 140 km/h (68, 75, 81, or 88 mph). They were calculated simply by assigning all the speeds above the speed limit to that upper speed limit. As might have been expected, an upper speed limit will have virtually no effect on the mean speed in the case of heavy traffic volumes. More surprising is the likewise almost insignificant impact that the speed limits have on the mean speeds at lower traffic volumes.

A speed limit of 120 km/h (75 mph), possibly marked as 110 km/h (68 mph), i.e., corresponding to the present situation in Denmark, should according to Table 2 cause the mean speed to drop at most by 2 km/h (1.2 mph). Circumstances, however, indicate that the mean speed would not decrease at all but would possibly even increase. In the morning traffic situation it appears that almost all motorists who drive at speeds faster than 120 km/h (75 mph) travel in lane 1, the left lane. A 120-km/h speed limit would have the following effect on the mean speeds of the two lanes:

1. Lane 1, reduction from 116.3 to 110.0 km/h (72.2 to 68.3 mph) and
2. Lane 2, reduction from 89.9 to 89.5 km/h (55.8 to 54.6 mph).

In other words, the effect is confined to the speed conditions in lane 1. However, by removing all speeds higher than 120 km/h in lane 1, it becomes easier for drivers in lane 2 to make use of the traffic gaps in lane 1 for overtaking purposes. If only a few of the drivers in lane 2 would find it easier to make use of lane 1 for overtaking purposes, a speed limit of 120 km/h would hardly cause any decrease in the overall mean speed, all other factors being equal.

A speed limit would thus tend to bring about some leveling out of the speed benefits, with the added advantage of a possible increase in mean speed. The drivers who in a situation without speed limits are particularly prone to get into trouble are those whose desired speeds are around 90 to 100 km/h (56 to 62 mph). These drivers can easily be caught in a queue in lane 2 but may have difficulties in carrying out an overtaking maneuver in lane 1 because of the necessary acceleration to very high speeds. In practical terms, a speed limit would thus assist the drivers wishing to travel at 90 to 100 km/h in changing from the queue speed of 75 to 85 km/h (47 to 53 mph) to the desired speed at the expense of reducing to 120 km/h (75 mph) the speed of drivers wishing to travel at 130 to 140 km/h (81 to 88 mph). If the traffic flow also contains heavy vehicles, travel speed under queue conditions in lane 2 may become lower still, even with low traffic volumes.

This argument for lowering the very high speeds on the Elsinore Road has been based exclusively on considerations for the operational use of the road and has been confined to conditions at low traffic volumes. In a general assessment of the drivers' use of the road, however, it is also necessary to take another aspect into account, namely, the uncomfortably strenuous traffic environment, which can easily be obtained if the traffic is handled at an unduly high speed level, that is, both the high speeds at low traffic volumes and a lack of adaptation of speed and traffic volume at high traffic volumes.

CONCLUSION

The road traffic model presented for describing the traffic flow on multilane roads can be briefly summarized and characterized as follows: On the basis of a description of the action pattern of individual drivers, the average driver's freedom of movement under given external conditions is quantified in a Markov process by using the measurable variables of state probabilities and transition intensities. Inasmuch as there are correlations between these new variables and the conventional road traffic parameters, i.e., traffic volume and speed, factors that have a bearing on the traffic flow can be quantitatively assessed.

A concluding assessment, with suggestions for possible applications of the road traffic model, may naturally be based on a critical evaluation of the model technique that has been used. Fundamentally, the road traffic model represents a method of interpreting the results of observations; it therefore represents a method rather than a model and, as already emphasized, it permits a quantitative description or at least a quantitative comparison of different highway and traffic engineering situations to the extent to which these situations are reflected in the behavior of the drivers.

This paper has mainly concentrated on a traffic engineering application of the model by showing how the traffic flow is affected by changes in the traffic volume. In a broader context, the essential aspect in this connection is the use of the road facility by the drivers since any discussion about the degree of use and possibly about a traffic overload stands and falls after all with the methods designed to indicate whether the drivers' behavior is appropriate. It is thus shown how the distribution of motorists over the two lanes and their eagerness to change lanes and to achieve a more suitable distribution over the two lanes are decisive factors affecting road use.

Among direct applications of the model, mention may also be made of a number of tasks of a highly practical nature. The Highway Capacity Manual does not for example distinguish between calculations for bridges and tunnels and for normal sections of road. Investigations carried out on an old bridge across the Little Belt in Denmark (4) seem to show that a road across a bridge is governed by quite special conditions. The bridge has only a 5.6-m-wide (18-ft) carriageway and a maximum observed traffic flow of 2718 cars/h. The road traffic model here proposed can be used in an analysis of the behavior of drivers on this type of highway facility with a view to a formulation of capacity and service level data.

Another traffic engineering application of the model might be associated with an evaluation of the effect of heavy vehicles on the traffic flow, e.g., whether it is reasonable to count heavy vehicles in terms of passenger car units, whether the effect of heavy vehicles on the remaining traffic varies with the traffic volume and the service level, the effect of up and down gradients, and so on. These are problems that, apart from the calculations more concerned with traffic engineering aspects, also have a bearing on the geometric design of a road, e.g., criteria for the design of climbing lanes or third running lanes.

The application of the road traffic model to the assessment of aspects more concerned with road geometry has thus been mentioned. By way of example, an evaluation of the traffic flow on the Elsinore Road during hours of darkness has been discussed (1). State probabilities and transition intensities have been recorded after dark on the same day as the morning, midday, and evening traffic situations and have been compared with the values that might be expected under daylight conditions. On the basis of the comparisons it is possible to indicate a quantitative expression of the effect that the new conditions offer to the traffic flow. Such an examination might be used to determine the expediency of, for example, installing road lighting.

REFERENCES

1. J. Rørbech. The Multilane Traffic Flow Process: An Evaluation of Queueing and Lane-Changing Patterns, Based on a Markov Model. Road Department, Denmark Ministry of Public Works, Copenhagen, 1974.
2. L. Breiman. Data and Models in Homogeneous One-Way Traffic Flow. Transportation Research, Vol. 3, 1969, pp. 235-249.
3. Highway Capacity Manual—1965. HRB, Special Rept. 87, 1965.
4. J. Rørbech. Capacity and Level of Service of Danish Highways. Traffic Engineering and Control, Vol. 10, No. 9, Jan. 1969, pp. 462-469.

Discussion

A. G. R. Bullen, University of Pittsburgh

Røhrbech's paper provides a refreshing approach to traffic flow theory by making a conscious and effective effort to bridge the gap between theory and traffic engineering practice. This gap is of long standing. On the one hand, theoreticians have been most reluctant to grasp some of the realities that practice demands while, on the other hand, practitioners have relied too much on makeshift empiricism devoid of any theoretical base. Although the paper does not succeed completely in bridging the gap, the level of achievement is well ahead of many other attempts.

The Markovian model used as the theoretical foundation for the work is logical and provides one of the most effective ways of dealing theoretically with multilane flow. The most doubtful feature of the model is the assumptions about basic driver behavior. Their basis is doubtful, and I do not accept them intuitively at least. Whether the empirical results confirm the claimed behavioral structure depends very much on the rationale for the development of these attributes and on whether any alternative structures were examined. These points are not clear. Although this is a possible weakness, it does appear that it need not be so, since it should be possible to formulate a model that is independent of behavioral assumptions at the micro level and that has a more generalized application to varying roadway geometries.

The empirical base for the model's calibration is limited, and broad-ranging interpretations or conclusions cannot be made at this stage, although the basic opportunity for further empirical work is provided. The model is valid for only two lanes of traffic, and there must be questions when the flow is extrapolated into the boundary of the congested flow region. It is this region that current empirically based models handle least well, and the present model, while pointing to some innovative methods of approaching the problem, needs much more validation. In this latter regard, the applicability of a Markovian model to the congested flow regime is extremely uncertain without considerable care in defining the random variable.

The development of capacity and level-of-service projections is the most interesting part of the applied work. The regression approach developed is innovative and worthy of extension although the limited empirical base limits the immediate strength of the results. Confirmation of the choice of the parabolic relationship would be desirable inasmuch as this is important in making the extrapolations and the empirical foundation is sparse.

In conclusion, I congratulate the author on his innovative look at several important areas of traffic engineering practice. It will, I hope, generate additional efforts to provide more satisfactory theoretical bases to the real world of traffic.