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Organization of Traffic Flows Simulation Aimed at Establishment of Integral Characteristics of Their Dynamics

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Abstract: The paper presents an approach aimed at the study of various aspects of traffic passage through a multi-lane road that is based on computational experiments. Microscopic simulation based on models of the type “leader-following models” is considered to be the most adequate and the most accurate means for performing them. The leader-following model of the entire traffic flows in a city road network acquires the more holistic form via the formalism of hybrid dynamic systems or, in other words, event-switched systems. The general formalization of this approach is presented and the corresponding representation of multi-lane traffic according to this approach is presented. The latter includes the detailed formal description of the traffic flow carrier with a certain traffic organization as well as the description of conditions for drivers’ choice of acceleration/braking and lane change according to incentive motives for it and positions and speeds of neighboring vehicles and the vehicle itself. Organization of computational experiments allowing to establish the dependence of the average speed of traffic on the density of incoming flows, the distribution of various types of vehicles and their drivers, road organization and other factors in a multi-lane road is considered. It is demonstrated in what way they allow to evaluate quantitatively the dependence of the road throughput on the above factors. Results of calculations are presented and analyzed.

Keywords: hybrid systems; traffic flows; leader-following model; city road network; multi-lane traffic; computational experiments.

1. INTRODUCTION

The city road network (CRN) as a whole and its individual segments limit satisfaction of transport needs of the population, which is expressed in slow motion, time waste in traffic jams, rejection of some desirable trips or choosing an uncomfortable time for them. Effective use of the throughput of the existing CRN and its fragments, as well as substantiation of measures to increase it, requires knowledge of the characteristics of individual roads and crossroads with the existing traffic organization and alternative options. Meanwhile, these characteristics are approximately known only for the most elementary cases. So, for single-lane traffic, estimates of road throughput have been established, ranging between 2000 and 2790 vehicles per hour [6, 8]. The variance of estimates is related to the difference in driving culture and the use of a different fleet of cars and trucks, and these differences can manifest even within one megacity. The use of road throughput is also affected by the distribution of trips between transport correspondences, almost always preventing the full load at the maximum level of all roads and their lanes.

The busiest highways carrying the bulk of the traffic flow (TF) are characterized by multi-lane movement. Multi-lane traffic also results in complex organization of motion at crossroads, for which a number of types are distinguished [3]. Integral characteristics of the flow through homogeneous segments of roads and crossroads depend on many circumstances and numerical characteristics of the TFs, including the proportions in which the flows are divided between directions in the nodes of the road network, as well as location of segments of allowed passage between the lanes and parking along the roads. So it quite impossible to establish integral characteristics of TF dynamics directly from treatment of observed data because of multidimensionality of affecting factors. However, systematical observations must be the source of needed data concerning elementary components of TFs (such as motion of a pair of successive cars) on a representative set of drivers and vehicles.

Physical-style theories, like widely known three-phase traffic theory by B.S. Kerner [4] yield the qualitative picture of the traffic phenomena but hardly may take into account all the affecting details. Another way to establish the necessary integral characteristics of TF is realized by mathematical modeling (analytical or, more often, by simulation). In this area both macroscopic models (e.g., the modern versions of hydrodynamic LWR models [2]) and microscopic ones exist. The latter, in turn, may be relatively rude cellular automata based on discretization of space and time [5] or much more realistic models in terms of dynamic systems that unite the movements of individual vehicles described with ODEs subject to additional servo-links.

The conceptual basis for modeling TF as a dynamic system is the “leader-following model”, the latter being a formal description of the vehicle control choice by a driver depending on the movement of the previous one [6]. The paper [3] put forward the way of integration of these particular models together with conditions resulting from traffic light regulation in the in the holistic model. The next step of evolution of this approach is the expression of such models via the formalism of hybrid systems [7].

This way of TF modelling may be applied to multi-lane traffic as well, but in that case the “leader-following model” must be coupled with a “lane-changing model” [6]. The paper presents the construction of such a model and the way to organize computational experiments with it and treat their results to obtain integral characteristics of TF dynamics.

2. GENERAL APPROACH TO TRAFFIC MODELING VIA THE FORMALISM OF HYBRID DYNAMICAL SYSTEMS

The analytical study of the TF dynamics within the framework of the “leader-following model” is limited to simple cases, mainly related to the so-called homogeneous congested traffic along one lane with a number of limiting assumptions, the main one being the identity of vehicles and their drivers (for example, [6]). The same models can be used via simulation. Advantages of such models of private TF modes consist in the explicit formulation of all interrelations. Undoubtedly, modeling by computer simulation has repeatedly been used to investigate more complex regimes, but only in the form of agent modeling, which treats relationships between the movements of neighboring vehicles as some forms of interaction between them. However, an integrated description of such an interaction may be absent; in any case, it is clearly not formulated in publications and therefore gives no possibility for critical analysis. With respect to verification of any agent modeling system, if it was fulfilled, one cannot be sure whether it is the result of a really correct reproduction of the nature of the transport processes or a successfully performed parametric identification (in other words, fitting) of the working model for specific conditions.

In accordance with common sense traffic members are considered as “vehicle–driver units” (VDU) [6], i.e., specific vehicles that are controlled by specific drivers. The proposed approach does not postulate a specific model for a separate VDU and its choice of motion direction (in the case of a shift between lanes, a stop for parking, or a crossroad pass) in interaction with the movements of neighboring vehicles. Such elementary relationships, obtained empirically, can be integrated into the resulting TF model for the road network segment, provided they are expressed in the required form. The model also includes a formal representation of the traffic organization on the segment of the road network being studied. In this sense, not a specific model of the TF is proposed, but a metamodel, which, however, is uniquely concretized to a specific TF model under specific conditions when using the required model elements characterizing the conditions being considered definitely or presumably.

Components of the model are:

1. formal description of the TF carrier furnished with the means of traffic regulation (traffic lights, barriers) and the conditions for the permissibility of trajectories along TF carriers;

2. formal description of the dependencies that determine the drivers' choice of control when driving on a standard trajectory;

3. formal description of the conditions for drivers' choice of the direction of movement;

4. description of the input streams (inflows) and their links with outflows that means distribution of VDUs entering the road network in consideration in a certain on-ramp between out-ramps.

1. The TF carrier is a segment of the road network in a detailed description. Permissible directions of motion on crossroads must be indicated; for a multi-lane road they must be determined for each lane. Each crossroad is described by its own network, or a "route web", uniting permissible trajectories that connect the all permitted pairs of entering lanes ends and beginnings of exit lanes. Points of their intersection must be indicated as well. For regulated crossroads, it is indicated for each trajectory at which phase of the traffic light cycle movement along it is permitted. If parking is allowed on the road segment at the road edge or in special parking pockets, the totality of such parking spaces is also treated as a lane. In general, the carrier is represented by an oriented labelled graph G with some peculiarities. They consist in the fact that each arc (oriented edge) of G, representing a certain lane, is assigned to a certain road segment and it is determined which lanes (if any) of the same segment are adjacent to it on the left and on the right. An arc may allow (along a certain zone of its border) the shift of VDUs moving along it to the adjacent lane. Zones of permissible transitions must be determined; they are treated as labels of arcs. Arcs of a crossroad "route web" connecting the same road segments are also grouped into a segment of the crossroad network.

The transition between arcs that do not belong to the same road segment is possible only at the points of their joining, i.e. at the end of the entering arc, coinciding with the beginning of the outgoing arc. These points are the vertices (nodes) of the graph G. Intersection points of admissible trajectories at crossroads are considered as vertices (nodes) of the graph G only if through such a point the VDUs travelling along more than one admissible trajectory may pass within certain time intervals. The latter is characteristic only for unregulated crossroads. In view of the inability to simulate the TFs in their natural limits (then we would have to consider the road network from Vladivostok to Lisbon), a fragment is cut from the network into which the VDUs enter from outside through the in-ramps and exit outside through the out-ramps.

2. Each edge of G at each instant of time contains a chain of vehicles, treated as a moving, and sometimes a motionless queue. The concept of a hybrid system means mixed, discrete-continuous dynamics. Discrete dynamics in models of this type include the change of the set of VDUs in some queue, as well as the change of the traffic light phases and the mentioned below modes of motion of individual VDUs.

The dependencies defining the control laws (in the sense that this concept has in the control theory) for VDUs are based on safety conditions. The most important and mandatory condition of safety is aimed to exclude the collision with the previous car and can be expressed as a formula of safe distance depending on the speed of this and, possibly, the previous car. It is supplemented by the conditions of speed reduction on curved sections of the road, as well as by the conditions of braking on the red phase of the traffic light (for the vehicle at the head of the queue). In the transition between the lanes, parking on the roadside, the safety condition is modified. Another condition for control choice is determined by the restriction on the speed and the desired (for public transport means — the normative) speed (they are distinguished if the latter is less than the maximum allowed speed).

It is assumed that the forms of the required dependencies are the same for all VDUs, but have parameters whose values are different for different types of VDUs. Various researchers developing “leader-following models” treat in the same way the general nature of these dependencies: the safe distance measured from the front bumper of the follower to the leader’s rear bumper depends on the speeds of both. The parameters of the dependence are the characteristics of the driver (first, its reaction time) and the vehicle of the follower. It is more convenient to consider the safety conditions with respect to the distance between the front bumpers of both (their positions relative to the current lane start are denoted by $s_{i-1}(t)$, $s_i(t)$ and serve as phase variables in the dynamic system of the TF). Then we need to add the length of the vehicle- leader to the “natural” distance. It is assumed, therefore, that the basic safety conditions

$$s_{i-1}(t)-s_i(t)\geq S_{\text{SAFE}}(v_{i-1}(t),v_i(t),p_i,p_{i-1}) \tag{2.1}$$

are satisfied permanently for all pairs “leader-follower”. Together with (2.1) for curved sections of the road, restrictions on the speed are considered depending on the local curvature CRV(s):

$$\dot{s}_i \leq V_{\text{SAFE CRV}}(CRV(s_i(t))). \tag{2.2}$$

In addition, there is a restriction similar to (2.2), on the maximum speed dictated by the traffic organization; they both can be combined in the form (2.2). The prohibition of entry to a crossroad when the traffic light is red means zero speed of the first vehicle in the lane at the moment of reaching the crossroad border and further until the green light turns on. Obviously, this condition is one of those that make hybrid the dynamic system of a TF: the leader of the queue changes the mode of motion from braking (until reaching the border of the crossroad) to a stop and then to acceleration from the moment when the green light turns on.

Such qualitatively different situations for choosing control are various but few). They are: acceleration at free movement when a speed is less than the desired speed; maintaining the latter; in the case when the minimum safe distance to the consequent VDU is reached — maintaining this distance; braking before a traffic light, or when stopping for parking, or when approaching a turn; transition between the lanes. For each of these cases the definite law of control acts, in other words, a definite motion mode. For each VDU, the current mode is treated as a variable of the qualitative state; other such variables characterize the position on the graph G (arc number) and the sequence number in the chain on the arc. The variables that characterize the current and forthcoming directions of motion may also be treated as variables of the qualitative state as well. Together with the regulator states, they form the vector of the qualitative state d of the simulated TF as a whole.

The movement (or its expectation) of all VDU in constant modes for some time eventually leads to a change in the mode of one or several VDUs or a change of the VDUs set for some chains. The transition from one mode to another is caused by the achievement of a certain boundary (hypersurface) in the combined phase space of the VDU (and perhaps of the adjacent VDUs) extended by the variable of the current time. For example, the condition for reaching a certain speed, approaching the minimum safe distance, starting the braking before the red traffic light signal from the stopping condition at the crossroad boundary under normal acceleration of braking (similarly when trying to occupy a free parking place) are all obviously conditions of that type. The same type of conditions determine the change in the of the VDUs set for chains: reaching the end of the lane by the head of the chain; termination of the shift of a certain VDU between lanes at the moment of when the lateral coordinate reaches its final value; entering the network by a next VDU from the on-ramp at a certain time instant. All these changes are traditionally known for hybrid systems as switches. It should be emphasized that the conditions of each switch, in addition to the switching hypersurface, are also characterized by the set of values of some components of the vector *d*. So, braking before the crossroad at red light begins only with the shift to the corresponding phase of the traffic light; formally it means the change of the proper component of *d*. To start a shift between lanes or a parking process, the conditions are not limited to one component of *d*.

All previously listed switches — changing the driving mode by a separate car, entering or leaving one TF in question, switching traffic lights at the end of the road — are considered as events of a stage change. Within the stage the phases of all traffic light cycles, the number of vehicles on each arc, the mode of each vehicle remain unchanged. As moments of switches are not known in advance, the same holds for time limits $[T(l\text{-}1), T(l))$ for each (l-th) stage. The discrete state variables in the l-th stage are combined into the vector $d(l)$, the phase variables characterizing the positions and speeds of the vehicles at the time moment t during the l–th stage — into the vector $x(t,l)$, its components for the i-th vehicle form vector $x_i(t,l)$. Dimensions of both $x(t,l)$ and $d(l)$ and even of certain $x_i(t,l)$ vary from stage to stage, since the latter includes the coordinate and the speed of movement in the transverse direction only during the transition between lanes. Constant values characterizing individual vehicles and driving them, including the purpose of movement, are also treated as components of $d(l)$.

To describe the dynamics of an individual vehicle, the generic representation is used

$$dx_i(t,l)/dt = f_i(d(l), x(t,l), U_i(d(l), x(t,l))) \tag{2.3}$$

in which one or more components of $d(l)$ characterize the motion mode, and the formula expresses the control law for this mode. It seems most natural to use acceleration as a control variable.

The conditions for determining the type $j(l)$ and the moment $T(l)$ of the switch that completes the l-th have the general form

$$g_{j(l)}(d(l), x(t,l), T(l)) = 0, j \in J(d(l)),\ g_j(d(l), x(t,l), T(l)) < 0, j \in J(d(l)) \backslash \{j(l)\}, \tag{2.4}$$

and follow from restrictions of type (2.1), (2.2). The result of switching is the change of the set of qualitative state variables

$$d_i(l+1) = D_{j(l)}(d(l)), i \in I_{D\ j(l)}(d(l)) \tag{2.5}$$

together with, maybe, some phase variables

$$x_i(T(l), l+1) = X_{j(l)}(d(l), x(T(l), l), T(l)), i \in I_{X\ j(l)}(d(l)). \tag{2.6}$$

Formula (2.6), in particular, refers to the longitudinal coordinates that change when passing from one arc to another ($s_i(T(l) = 0$), since they are now measured from the other point. The similar change takes place for the transverse coordinate at the time of completion of the transition to a new lane.

However, a mode change may require certain values of several components of $d(l)$. In this case, it occurs at the moment when the last one receives the required value. This moment is also determined by the condition (2.4) for a component of $d(l)$, but only for the case when all other ones already have the required values (and do not change them at the last switching). However, it doesn't not matter which component of $d(l)$ is the last to get the required value.

This does not require the modification or addition of the relations (2.4)–(2.6), but only their detailed specification. Namely: a change in the regime of a specific vehicle can be made for different combinations of $j(l)$ and $d(l)$, but in all cases, the value of the corresponding component $d_i(l+1)$ expressing the motion mode of this vehicle, in all cases, will be the same.

3. The current direction of movement of a specific VDU is characterized by the goal of stopping at the current section or continuing to move on reaching the end of the current segment for a certain new segment. Hence, according to the current scheme of traffic

organization, this goal results in the task of transition to the lane from which it can proceed to this new segment.

The overall goal of a particular VDU is to reach a specific target point (off-ramp) or to park in a certain area. With the exception of public transport, in most cases it is possible to choose a route. In practice, it is possible either to pre-select a route or to select it step by step when receiving information about the status of TFs, which, however, does not guarantee the choice of the most effective route. If we take as a basis any method of forecasting the duration of the route according to the current and historical data, then its recommendation will be reduced to the proposal to select the same next section for all VDUs having the same target node and currently passing a certain node. Each such recommendation is expressed by a variable that has the properties of a component of d and, apparently, can somehow be calculated within the same formalism, although it is unlikely that the method of calculating it will be relatively simple (for some forecasting methods, the computations that realize them are guessed, but confirm the assumption about their complexity and high amount of calculation). We retain such an option as possible in principle, but at the present stage of research we confine ourselves to a more realistic way of modeling the behavior of drivers, namely by assigning each of them a certain route (with detailing to the sequence of passing the sections of the road network).

3. MODELING OF TRAFFIC ON A MULTI-LANE ROAD

In accordance with the objectives of the study, a one-way multi-lane road from the CRN is selected for study, it is bounded at both ends by crossroads (junctions) and not contains them within itself. The traffic organization can allow vehicles to leave the TF and enter the TF only from parking places along a part of the length of the road. Parking spaces are collectively considered as the rightmost lane of a road, traffic on which is not allowed. Regarding the transitions between the lanes, the segments of each lane on which passages through its left or right border are permitted (including for parking purposes) are defined. In addition, the destination of the end segment of each lane is defined as to carry out further movement in a certain direction or directions (right, left, right). Limitations on traffic for each lane include: maximum speed and category of vehicles (passenger car, bus, freight with a certain weight limit) for which movement along it is allowed. The definite number of categories is introduced.

For each individual participant (VDU) of the simulated TF, the following parameters are specified: 1) category; 2) the purpose of the movement, namely the direction of movement when leaving the lane or the intention to park along the road; 3) the length; 4) a set of indicators that determine the dynamics and driving, including perception of the minimum safe distance to the leader.

It is assumed that to achieve its goal, each driver uses several driving modes. In the process of moving along one lane these modes are: 1) acceleration up to the maximum (desired) speed, 2) maintaining the desired speed; deceleration aimed at 3) stopping at a given place or (for a curved road) at 4) non-exceeding the safe speed; 5) maintaining the minimum safe distance to the leader. In the process of transition between the lanes, the variants of the same modes are implemented, but the conditions for the maintenance of the minimum safe distance are modified, since it is calculated to the nearest leader on the old and new lane. Each mode is assumed to be expressed by the corresponding model law of control (acceleration/deceleration). The change of driving mode by a separate vehicle, entering or leaving the TF in question by a vehicle, switching traffic lights at the end of the road are considered as events of phase change; within the phase of the phase of the traffic light cycle, the number of vehicles, the mode of each remains unchanged.

For the 1st mode, the "normal" (for a specific VDU) acceleration ($U_i(d(l), x(t,l)) = a_{\mathrm{NORM}\,i}$) and for the third one "normal" deceleration

($U_i(d(l), x(t,l)) = -b_{\text{NORM}\,i}$) are accepted, for the 2nd one the uniform motion ($U_i(d(l), x(t,l)) = 0$) takes place. For the fourth mode, the acceleration is determined from the motion condition at a safe speed ($U_i(d(l), x(t,l)) = dv_{\text{SAFE}\,i}(s_i(t))/dt$). In all these cases, there is no dependence of the control of the VDU on the phase coordinates of other VDUs, which expresses the specifics of a TF as the interconnected motion of many of its participants. In the fifth mode, this specifics is present, but can be expressed in different ways.

The movement of a vehicle is considered, first of all, along the axes of the road lanes. Even in the passage to another lane, the trajectory is directed at a small angle to the axes of adjacent lanes and the longitudinal velocity is practically equal to the actual velocity; the change in velocity during the transition time can be neglected. Therefore, with respect to the quantitative dynamics, we may reduce representation of the VDU dynamics to the equations of longitudinal motion with respect to the current position of the vehicle s_i measured along the axis of the lane, namely

$$ds_i(t, l)/dt = v_i(t, l); \qquad dv_i(t, l)/dt = a_i(t, l), \qquad a_i(t, l) = U_i(d(l), x(t,l)). \tag{3.1}$$

For any representation and for any of the above modes, switches between them occur when the condition represented with one equation is satisfied, which parameter may be components of the qualitative state in the mode before switching.

So, to complete the set of speed and transition to a uniform motion, this is just a condition

$$v_i(t) = v_{\text{MAX}\,i}, \tag{3.2}$$

for inclusion in the cluster and transition to the fifth mode —

$$s_{i-1}(t) - s_i(t) = S_{\text{SAFE}}(v_{i-1}(t), v_i(t), p_i), \tag{3.3}$$

similarly for switching between the fifth mode options. To start the transition, the transition conditions are somewhat more complicated.

Let us first formulate the conditions for the beginning of the transition at the content level. The condition for the possibility of a transition is: the admissibility of such a transition (the intersection of the dividing line in the direction of the new lane); presence of sufficient advance of the potential "follower" on the adjacent strip $\Delta s(k)$; presence of motivation for transition under conditions of speed advantage, consisting in that the safe distance to the leader on the neighboring strip exceeds the safe distance to the leader on the current lane by at least; the presence of motivation for the transition to the conditions of the timely occupation of the lane, at which the vehicle under consideration is required to be located at the end of the present road segment. The moment of the onset of each of the conditions, as well as the moment when the previously fulfilled condition is violated, are determined, as above, from relations of the form (2.4), the parameters of which relate to the considered VDU, preceding on the strip and conditional leaders and followers for it on adjacent lanes.

The moment of the shift beginning begins a stage that is characterized with additional coordinates and equations for lateral motion and additional relations between (security conditions are associated with a tuning vehicle with its "leader" and "follower" on both strips). With respect to the VDUs the lateral coordinate, the condition for the termination of the transition is recorded, the result of which is the change in the order of the VDU on both lanes and the restoration of the old system of constraints with new parameters.

4. ORGANIZATION OF COMPUTATIONAL EXPERIMENTS

In accordance with the research objectives, in a separate computational experiment, the TF dynamics are calculated with definite and on average constant values: 1) the intensity of the input flow (and exit from parking places along the road, if it is allowed); 2) the proportions between the target directions in the input stream; 3) the composition of the input stream (in the simplest case - the shares of the introduced categories of vehicles). In accordance with the selected values of the experimental constants listed above, the characteristics of the individual vehicles of the input sequence and the time intervals between their appearances are randomly generated.

A separate experiment begins with an empty road gradually filled with vehicles. Flow characteristics are calculated in steady state when the road is completely filled. Average characteristics and their dispersion for a sufficiently long period are determined. In the case of simulation of the application of traffic light regulation, the dynamics of the TF for a period after reaching the steady state, a multiple of the duration of the traffic light cycle is considered.

The result of the calculation is the sequence of values of the components of the vectors $x(t,l)$ and $d(l)$. At the same time, these quantities can be stored in the database, but only integral indicators of flows along the lanes.

Initial data for the computational experiments are recorded in the database tables (see tables 4.1 and 4.2) and extracted from them for TF simulation. They characterize both the content conditions of the experiments and calculation parameters (see the maximal step Δt_{MAX} for integrating motion equations in table 4.1).

Table 4.1. General data for computational experiments

Expt.	Δt_{MAX}, s	T_{MAX}, s	Averaging interval, s	Q_{LANE}, VDUs per hour	$\sigma_{\Delta t\ IN}$
tst011	0,5	300	10	1500	0,5
tst011A	0,5	600	10	1500	0,5
tst021	0,5	300	10	2000	0,5
tst021A	0,5	420	10	2000	0,5
tst021B	0,5	420	10	2000	0,5

Table 4.2. Data on VDU types in computational experiments

Expt.	VDU type	a_{NORM} i; b_{NORM} i	Length; width	v_{OPT}, m/s	T_{REAC}, s	$\sin\alpha$	Type quote in on-ramp flow
tst011	1	4;;7	3; 1,8	25	0,3	0,1	75
tst011	2	2; 4	10; 3	17,5	0,2	0,15	25
tst021	1	4; 7	3; 1,8	25	0,3	0,1	75
tst021	2	2; 4	10; 3	17,5	0,2	0,15	25

The character of the TF dynamics is ambiguous and depends on the characteristics of the ATP (see tables 4.3, 4.4). At a moderate TF intensity (in the examples it is 1500 VDU/h per one lane), flow characteristics are stable, although deviations from the mean values take place permanently preserved. With the equivalence of the lanes, neither one gets an advantage.

Table 4.3. Statistics on ATP, a series of experiments “tst011”

Expt.	T_{BEG}	T_{END}	Mean VDUs count	Mean VDU speed	VDUs in shift, %
tst011	20	300	11,75	21,36	8,81
tst011A	20	300	12,18	20,78	9,94
tst011A	300	600	12,55	20,85	10,97
tst011B	20	300	11,92	21,08	9,67
tst011B	300	600	11,72	21,18	8,00

Table 4.4. Statistics on ATP, a series of experiments “tst011”

Expt.	T_{BEG}	T_{END}	Mean VDUs count		Mean VDU speed	
			1st lane	2nd lane	1st lane	2nd lane
tst011	20	300	6,02	5,73	21,50	21,18
tst011A	20	300	5,95	6,23	20,71	20,81
tst011A	300	600	6,46	6,10	20,64	21,01
tst011B	20	300	6,26	5,66	21,47	20,51
tst011B	300	600	5,74	5,88	20,93	21,44

On the contrary, the flow approaching its maximum intensity is unstable (see tables 4.5, 4.6), queues at the entrance and supersaturation of the road section can be formed. In this case, the speed can drop sharply. These phenomena are well known, but modeling by simulation allows determining the conditions of their occurrence (depending not only on the intensity of the flows, but also on their composition with respect to VDU types).

Table 4.5. Statistics on ATP, a series of experiments “tst021”

Expt.	T_{BEG}	T_{END}	Mean VDUs count	Mean VDU speed	VDUs in shift, %
tst021	20	300	19,18	17,36	12,72
tst021B	20	300	16,81	19,53	11,13
tst021B	300	400	22,35	9,62	24,95

Table 4.6. Statistics on ATP, a series of experiments “tst021”

Expt.	T_{BEG}	T_{END}	Mean VDUs count		Mean VDU speed	
			1st lane	2nd lane	1st lane	2nd lane
tst021	20	300	9,79	9,38	17,25	17,52
tst021B	20	300	8,07	8,74	19,31	19,68
tst021B	300	400	9,75	12,61	11,59	8,30

Repetition of a series of experiments with different values makes it possible to obtain a series of data for the characteristics of the unknown dependencies that are interpolated to the range of interest.

5. CONCLUSION

The paper presents the general approach to establishment of integral characteristics of traffic flow dynamics, notably for multi-lane roads, and illustrates it in the case of two-lane traffic with a relatively simple road organization. With the development of this approach more sophisticated integral characteristics of multi-lane TFs must be obtained, including the influence of the structure and parameters of the traffic light cycle at the end of the road in question and the distribution of VDUs between desired directions of subsequent passage of the road network.

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