States of Traffic Flow in Deep Lefortovo Tunnel (Moscow): Empirical Data

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Traffic flow in long tunnels

Traffic flow dynamics in long highway tunnels has been studied individually since the middle of the last century (see, e.g., Refs [1, 2]). Interest to this problem is due to several reasons. The first and, may be, main one is safety. Jam formation in long tunnels is rather dangerous and detecting the critical states of vehicle flow leading to jam is of the prime importance for the tunnel operation. However, the tunnel traffic in its own right is also an attractive object for studying the basic properties of vehicle ensembles on highways because, on one hand, the individual car motion is more controllable inside tunnels with respect to velocity limits and lane changing. On the other hand, long tunnels typically are equipped well for monitoring the car motion practically continuously along them, which provides a unique opportunity to receive a detailed information about the spacial-temporal structures of traffic flow.

By this paper we start analysis of the basic properties exhibited by tunnel congested traffic that is based on empirical data collected during the last time in several new deep long tunnels located on the 3-rd circular highway of Moscow. Here preliminary results for the Lefortovo tunnel (Fig. 1) are presented. It comprises two branches and the upper one is a deep linear three lane tunnel of length about 3 km. Exactly in this branch the presented data were collected. The tunnel is equipped with a dense system of stationary radiodetectors distributed uniformly along it chequerwise at spacing of 60 m. Because of the detector technical features traffic flow on the left and right lanes is measured at spacing of 120 m whereas on the middle lane the spacial resolution gets 60 m. The data were averaged over 30 s.

Each detector measures three characteristics of the vehicle ensembles; the flow rate \( q \), the car velocity \( v \), and the occupancy \( k \) for three lanes individually.
The occupancy is an analogy to the vehicle density and is defined as the total relative time during with vehicles were visible in the view region of a given detector within the averaging interval. The occupancy is measured in percent.

**Observed cooperative motion of vehicle ensemble**

This section demonstrates that the observed traffic flow indeed exhibits cooperative dynamics when the vehicle density becomes high enough. To do this figure 2 (upper frames) depicts the phase planes $\{k, v\}$ and $\{k, q\}$ with the distribution of the traffic flow states fixed by all the detectors on 31.05.2004. These phase planes were divided into cells of size about $1\% \times 2$ km/h and $1\% \times 0.02$ car/s, respectively, and the number of states measured with frequency $1/30$ s$^{-1}$ and falling in a chosen cell were countered, giving the corresponding distributions. These distributions in some relative units are represented here in the form of the level contours. The left side of each window matches the free flow states as clear seen in the right window, where the darkened region visualizes an upper fragment of the flow-density relation of the free car motion. However the obtained distributions even for the free flow are widely scatted which seems to be due to the essential heterogeneity of the free flow with respect to the headway distances. The middle parts of these windows visualize another mode of traffic flow corresponding to the so-called widely scattered states or the synchronized vehicle motion (for a review see Refs \cite{3, 4}). In fact here the distribution levels cover rather wide regions and do not follow each other so frequently as in the left part. Exactly this mode is usually related to the cooperative vehicle motion.
Figure 2 (lower frame) exhibits the spatial autocorrelations in the occupancy, car velocity, and flow rate measured by differing detectors vs the distance between them (lower frame).

Figure 2 (lower frame) exhibits the spatial autocorrelations in the occupancy, car velocity, and flow rate measured by different detectors at the middle lane on 28.09.2005 when congested traffic was dominant. In agreement with the single-vehicle data [5] the congested vehicle motion is characterized by essential correlations especially in the car velocity. The flow rate measurements are correlated substantially only within several neighboring detectors (on scales about several hundred meters) whereas the velocity measurements as well as the occupancy ones are correlated at half of the tunnel length, i.e. at scales about one kilometer.
Pattern of vehicle ensemble dynamics in the phase space

The characteristics of the vehicle ensemble dynamics in the phase space \( \{k, v\} \) were studied in the following way, replicating actually the technique of Ref. [6] used in a similar analysis. The plane \( \{k, v\} \) is divided into cells \( \{C\} \) of size 2.5% × 2.5 km/h. Let at time \( t \) the traffic flow measurements of a given detector fall in a cell \( C_i \) and in the averaging time \( dt = 30 \text{ s} \) the next measurements of the same detector are located in a cell \( C_j \). Then the vector

![Regularity of traffic flow dynamics, \( \mathcal{D}/\mathcal{N} \)](image)

![Drift field of traffic flow in phase space, \( \mathbf{V}_m \)](image)

**Fig. 3.** Structure of ensemble vehicle dynamics in the phase space \( \{o, v\} \). The upper window visualizes distribution of ratio between the random and regular components of the effective forces. The lower window depicts the regular drift field.
$$dr := \{dk_t, dv_t\}$$ such that $$dk_t = k_j - k_i$$ and $$dv_t = v_j - v_i$$ describes the system motion on the phase plane at the given point $$r_t := \{k_t, v_t\}$$ at time $$t$$. These vectors were calculated using the data collected on 28.09.2005 by all the detectors. Averaging the found vectors gives the drift field $$\mathbf{V}_m(r) = \langle dr \rangle / dt$$ and the intensity $$D(r)$$ of an effective random force determined as

$$D dt = \sqrt{\langle |dr| \rangle^2 - \langle dr \rangle^2}.$$ 

Figure 3 exhibits these fields. The upper window depicts the ratio $$\eta := D / |\mathbf{V}_m|$$, namely, its variations from 0 up to 3.5. The white region comprises the cells where no measurements were obtained. The hatched domain matches the ratio $$\eta > 3.5$$, where the vehicle ensemble dynamics can be regarded as pure random. The region between them contains several levels of the ratio $$\eta$$ variations and the level $$\eta = 1.0$$ is singled out in Fig. 3. For smaller values of $$\eta$$ the dynamics of vehicle ensemble becomes practically regular.

The lower window of Fig. 3 shows the drift field $$\mathbf{V}_m(r)$$. Since its intensity changes essentially at different parts of the plane $$\{k, v\}$$ two frames are used to visualize it. In the left frame the drift field is zoomed in by three times relative to the right one. Let us consider them individually. The system dynamics in the right frame is rather regular and the field $$\mathbf{V}_m(r)$$ corresponds to the irretrievable drift of vehicle ensemble to smaller velocities and higher densities. In other words, it is some visualization of the jam formation. In fact one or two jams were the case on that day. It should be noted that the transition region separating the left frame pattern being rather chaotic and the given one is relatively thin, it is located at $$k = 35\%$$ and has a thickness less then 5\%. So the observed jam formation seems to proceed via some breakdown in the cooperative vehicle motion, which is an agreement with other data [4].

The pattern shown in the left frame matches the upper one in structure. Inside a neighborhood $$Q_0$$ of the decreasing frame diagonal the traffic dynamics is practically pure chaotic, at least, the found values of $$\mathbf{V}_m(r)$$ are relatively small and their directions do not form any regular pattern. As it must, outside this domain the field $$\mathbf{V}_m(r)$$ becomes more regular and the obtained data enable us to estimate its characteristic direction. Unexpectedly, it turns out that the field $$\mathbf{V}_m(r)$$ crossing this neighborhood does not change its direction for backward one as it should be if the domain $$Q_0$$ has contained a zero set of the regular field $$\mathbf{V}_m(r)$$. Such behavior of a dynamical system can be explained using the notion of dynamical traps predicting also the existence of a long-lived state multitude as a consequence of some nonequilibrium phase transitions caused by the human bounded rationality [7, 8, 9].

**Conclusion**

The paper presents a preliminary analysis of traffic flow data collected in the Lefortovo tunnel located on the 3-rd circular highway of Moscow or, more
It is shown that the observed tunnel congested traffic in fact exhibits cooperative phenomena in vehicle motion, namely, there is a region of widely scattered states on the fundamental diagrams which is related typically to the appearance of synchronized traffic. Besides, the spatial autocorrelations in the occupancy, vehicle velocity, and flow rate measured by different detectors are found to be essential. Especially it concerns the correlations in the velocity and occupancy, their correlation length gets values about 1 km. The occupancy data are correlated on substantially shorter scales about 200–300 m.

The phase portrait of the vehicle ensemble dynamics on the occupancy-velocity plane is also studied. It is demonstrated that there are two substantially different regions on it. One matches actually the cooperative vehicle motion and contains some kernel where the dynamics is pure chaotic. It is essential that the found regular drift outside this region does not change the direction when crossing it. The latter feature is some prompt to applying the concept of dynamical traps to describing phase transition in congested traffic. The other part of the phase plane corresponds to the irreversible stage of jam formation. The two regions are separated by a rather narrow transition layer located at $k = 35\%$, which demonstrates that the observed jams originated inside a congested traffic via some breakdown.

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