Experimental study of short-range interactions in vehicular traffic

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Single vehicle data obtained from magnetic loops on an expressway allowed us to measure velocity correlations and velocity differences between non–neighbor vehicles on the same lane, showing some strong correlations even for platoons of 7 or 8 vehicles. The corresponding time headway distribution for non–neighbor vehicles is also presented. We were also able to get some informations about interlane structures, through crossed time headway distributions. It should be noticed that these last results on crossed time headways are meaningful only because the subset of data we used corresponds to a unique stationary traffic state and still contains a large amount of data, with a large fraction of short time headways. The link with passing maneuvers is discussed.

I. INTRODUCTION

The number of vehicles present on the road network has kept increasing in the past decades. Technology advances also modify the way of driving. More and more interest is devoted to traffic science and physicists are more and more involved in the field, especially at the connection between experimental measurements and modeling. This interest is in particular motivated by the development of new or more efficient measurement devices and by increased data storage capacities, which allow to have a more thorough insight into the structure of traffic.

At the microscopic level, while pair longitudinal interactions are now quite well known [1–7], there is still much to learn about lateral interactions [8–10] and also about collective effects—or correlations between vehicles, to state it otherwise [11–15]. This knowledge would be useful though, both in the perspective of modeling and of security improvement.

This paper focuses on short range interactions between vehicles, through the analysis of empirical single vehicle data collected by magnetic loops on a two-lane expressway (N118) in the suburb of Paris (France).

In a first stage, we shall study intralane velocity correlations and relate them to time headways, showing some strong collective effects. Actually, velocity correlations between distant vehicles had already been measured, as a function of the number of vehicles placed in between [11]. Here we obtain a much more precise measurement: for a given number of in between cars, we obtain the full curve giving the velocity correlation coefficient as a function of the time headway. This measurement requires a much larger data set in order to achieve sufficient precision. Note that in the whole paper, time headways are measured between the rear of the leading vehicle and the front of the other vehicle. While the time-headway distribution between successive vehicles has already been measured for example in [1,3,16–20], we shall plot it here for non–neighbor vehicles.

Then results about interlane structures will be presented, with a focus on interlane time-headway distributions, and

their link with passing maneuvers will be discussed. In order to perform these measurements, our data set had to fulfill several constraints. First, as we wanted to compare several interlane time-headway distributions, a necessary condition for our conclusions to be meaningful was that these distributions would be measured for a unique stationary traffic state. Second, as our interest was in short range interactions, we wanted the fraction of short time headways in this selected traffic state to be large. Eventually, as the above measurements require to select events with rather restrictive criteria, a large amount of data had to be retained in order to have good statistics.

These goals were achieved by selecting the 11 am–4 pm time window on a set of 46 week days. Indeed, the expressway is mainly used for daily commuting. On week days, while severe congestion occurs in the early morning and late afternoon, a quite homogeneous traffic state takes place from 11 am to 4 pm On the fundamental diagram, this homogeneous traffic state is located on the upper part of the free-flow branch, in the region where it starts to bend, in particular because of the interactions with slower vehicles. Indeed, the percentage of cars is, respectively, 85% (91%) on the right (left) lane. The remaining of the vehicles is mainly composed of trucks on the right lane, and of cars towing caravans or light trailers on the left lane. During the period of time from 11 am to 4 pm, some strong short range interactions are present; the fractions of vehicles which have a time headway below 0.5 s (respectively, 1 s) are 2.4% (respectively, 15%) on the right lane and 4.2% (respectively, 21.5%) on the left lane. The average velocity is around 90 km/h on the right lane and 110 km/h on the left lane (the legal speed limit is 110 km/h). Eventually we obtained a data collection with 266 173 vehicles on the right lane and 178 546 vehicles on the left lane—an amount of data which allows for good statistics. Data include, for each vehicle, its passage time, velocity, length, and some classification into cars, trucks, etc. Passage time refers to the passage of the front of the vehicle on the captor.

Vehicles on one given lane are numbered according to their passage order on the loop. This number will be called the rank of the vehicle in the remaining of the paper.

Throughout the paper, error bars were obtained by dividing the data into 5 subsets, computing the quantity of interest

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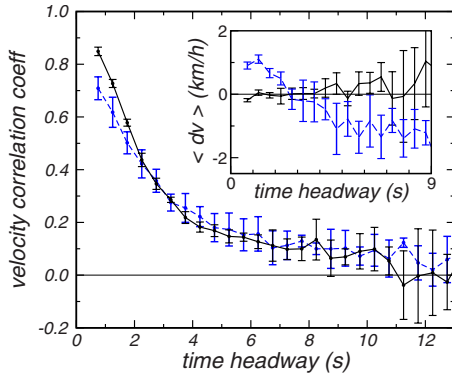*cecile.appert-rolland@th.u-psud.fr

FIG. 1. (Color online) For successive vehicles: Velocity correlation coefficient and (inset) mean velocity difference as a function of the time headway, on the right-slow lane (black solid line) and on the left-fast lane (gray—blue online—dashed line).

for each subset, and then the root mean square resulting from the five values. Error bars correspond to 2 root mean squares.

II. INTRALANE VELOCITY CORRELATIONS

The correlation coefficient between two variables v and $\tilde{v}$ is defined by

$$\text{c.c.} = \frac{\langle v\tilde{v}\rangle - \langle v\rangle\langle\tilde{v}\rangle}{\sqrt{[\langle v^2\rangle - \langle v\rangle^2][\langle\tilde{v}^2\rangle - \langle\tilde{v}\rangle^2]}} \tag{1}$$

This coefficient should be 1 (respectively, 0) for fully correlated (respectively, uncorrelated) variables.

First we have measured the velocity correlation coefficient for pairs of successive vehicles which have a time headway within the interval $[k\times0.5, (k+1)\times0.5]$ seconds. The results for $1 \le k \le 25$, presented in Fig. 1, show that short time headways induce strong velocity correlations—which is of course necessary in order to avoid accidents. An exponential fit $a_0\exp(-t_h/t_0)+a_2$ gives a correlation time scale $t_0 = 2.3s$ on the left lane and around 2 s on the right lane. A similar exponential relaxation is observed for the standard deviation of the velocity difference between successive vehicles.

As seen on Fig. 1 (inset), the velocity difference between successive vehicles has its average going to zero on the right lane, while on the left lane, it becomes strictly positive (around 1 km/h) for short time headways, as if vehicles separated by short headways were trying to increase their distance. The opposite phenomenon seems to occur for larger time headways, as if for $t_h > 4s$, vehicles were trying to catch up with their predecessors.

Instead of considering successive vehicles, we shall now consider pairs of vehicles separated by a fixed number n of other vehicles and repeat the same procedure. For example, in the case $n=3$, the time headway is defined as the passage time difference between the rear of the vehicle of rank i, and the front of the vehicle of rank i+4. While the maximum of the time headway distribution is around 10 s, quite short time headways (below 3 s) can still be observed (Fig. 2). The shortest time-headways are observed on the left lane, due to more aggressive driving.
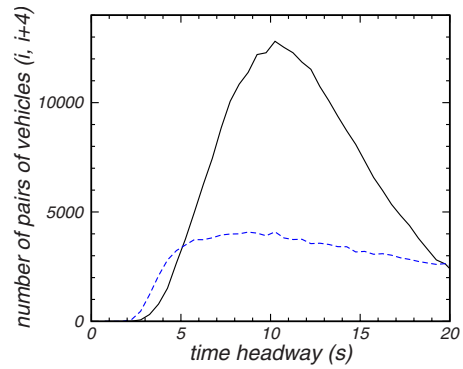

FIG. 2. (Color online) Distribution of time headways between vehicles of rank i and i+4, on the right-slow lane (black solid line) and on the left-fast lane (gray—blue online—dashed line).

In spite of the distance between the vehicles, velocity correlations are still very strong at short time headways, especially on the right lane (see Fig. 3). The characteristic time scale obtained from an exponential fit is now 3.6 s on the left lane and 3.1 s on the right lane, to be compared with the 3.5 s and 3.3 s obtained from the fit of the velocity difference standard deviation (Fig. 4). These results can be compared with those obtained for successive vehicles. We notice that, if we consider the velocity correlation of pairs of vehicles separated by a given time headway, it is higher when there are more cars between the two vehicles of the pair. Or, to say it otherwise, the data support an increasing velocity correlation with the increase in n (for a fixed time headway). In a certain way, the in between vehicles rigidify the binding between end vehicles. We could also say that they transmit information from one end car to the other.

The mean velocity difference at short time headways on the left lane (Fig. 4, inset) is now equal to about 3 or 4 times its value for successive cars. It is an additive phenomenon, each car trying to drive about 1 km/h more slowly than its predecessor.

We observe that platoons of vehicles on the right lane are formed behind a truck in about one third of the cases, while situations are much more varied on the left lane.
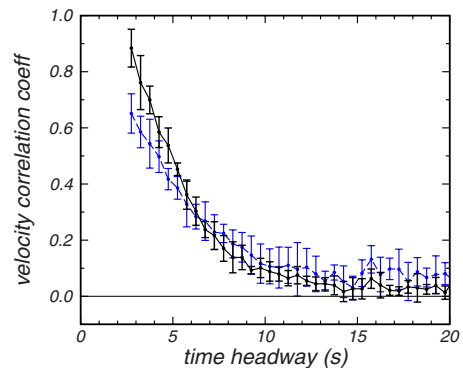

FIG. 3. (Color online) For pairs of vehicles of rank i and i+4: Velocity correlation coefficient as a function of the time headway, on the right-slow lane (black solid line) and on the left-fast lane (gray—blue online—dashed line).
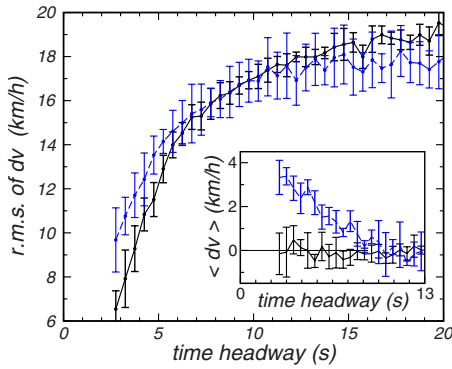
FIG. 4. (Color online) For pairs of vehicles of rank i and i+4: Standard deviation and (inset) mean of the velocity difference, as a function of the time headway, on the right-slow lane (black solid line) and on the left-fast lane (gray—blue online—dashed line).

Velocity correlation coefficients as large as 0.6 can still be observed between vehicles of ranks i and i+7 separated by a time headway of about 6 or 7 s (when the rank difference is increased further, results are too noisy to conclude). Thus quite long strongly correlated platoons can be observed in the flow.

III. ACROSS LANE TIME HEADWAY DISTRIBUTIONS

One important question when short time headways are observed is whether those are stable or only transients. A situation where one expects transient short time headways is when a vehicle prepares itself to pass another vehicle. We thus wondered whether vehicles that have a short time headway on the right lane indeed have an opportunity to change lane, i.e., whether there is a "hole" on their left.

We measured their time headway with the preceding vehicle located, not on the same lane, but on the left lane, as this is illustrated schematically on Fig. 5(a). As the preceding vehicle on the left lane may partially be side by side with the right lane vehicle [Fig. 5(b)], negative time headways can be measured. The resulting distribution must be compared with the distribution obtained by the random procedure described in Fig. 5(c). Note that, as the random passage time is chosen without any exclusion rule, the virtual vehicle and its (real) leader may partially overlap, thus negative time headways may again be obtained.

If one tries to guess the shape of the distribution resulting from this random procedure, two opposite effects can be expected: on the one hand, it is more likely that the random passage time will be chosen inside a *large* time interval separating the passage of two successive vehicles. Thus more importance should be given to large time headways. On the other hand, the random procedure "cuts" into two parts the time headways, thus the weight of small time headways should also be enhanced. Actually, both effects are observed. As seen on Fig. 6(a), if one compares the distribution obtained by the random procedure with the intra left lane time headway distribution, the maximum of the distribution is shifted toward small (even negative) time headways, while the tail at large time headways is less damped than for the intralane distribution.
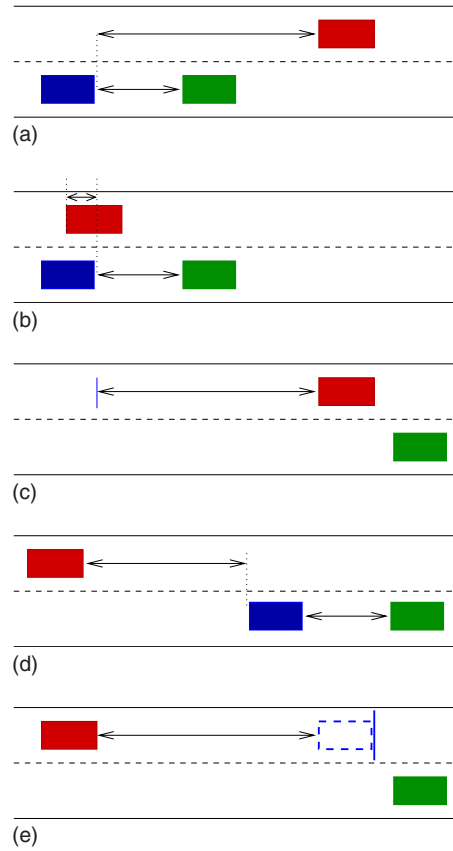

FIG. 5. (Color online) Schematic representation of the interlane time headway measurements, for a two-lane road. Vehicles are driving to the right. In panel (a), a time headway shorter than 0.5 s separates the two vehicles on the right lane. Then, the time headway between the right lane following car and its predecessor on the other lane is computed as indicated by the arrow (in all the schemes, a spatial representation has been substituted to the temporal one, though in practice, one computes the passage time difference between the rear of the left-lane vehicle and the front of the right-lane vehicle). Panel (b) illustrates how a negative time headway can be obtained: the front of the left lane vehicle went first on the magnetic loop (thus it is the leader of the right lane vehicle), but its rear arrived on the loop after the front of the right lane vehicle. In panel (c), the time headway is computed between a virtual vehicle whose location is randomly chosen, and its predecessor on the same (left) lane. The procedure is independent of the right lane state. Panel (d): same as (a), but it is the *successor* that is considered on the left-lane. Panel (e): same as (c), but the time headway is computed with the successor of the virtual vehicle. The ratio length/velocity of the virtual vehicle is chosen randomly according to the distribution of length/velocity ratios of the right-lane vehicles.

Now, when a short time headway (less than 0.5 s) is observed on the right lane, the time headway with the vehicle on the other (left) lane is likely to be much shorter than for a random procedure. Thus right-lane vehicles with a short headway are more likely to have a very near neighbor ahead (or aside) in the other lane.

At this stage, this does not necessarily mean that the right-lane vehicle does not intend to overtake, it could overtake just after its left leader. In order to explore further the possibilities that the right vehicle has of overtaking, we repeated
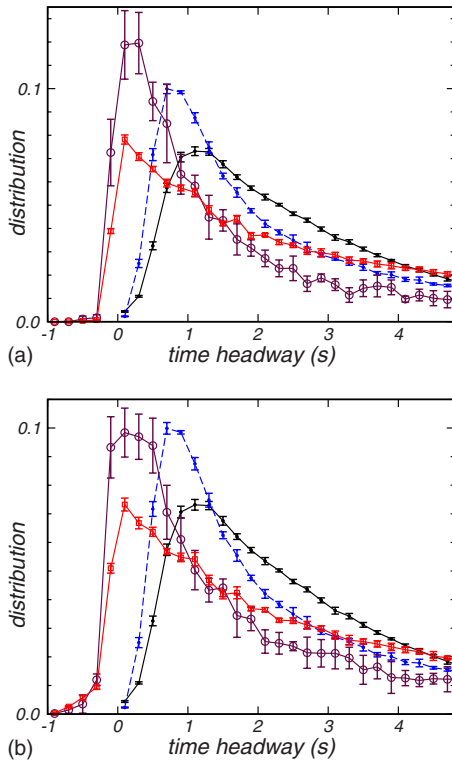
FIG. 6. (Color online) In both panels: intra right and left lane time headway distributions (respectively, solid black and dashed gray—blue online—lines). In panel (a): distributions of the time headway with the left-lane predecessor, for (maroon online—circles) the interlane procedure of Fig. 5(a), or for (red online—squares) the random procedure of Fig. 5(c). In panel (b): same as panel (a), but it is now the *successor* that is considered on the left-lane. The random procedure (red online—squares) corresponds now to the procedure of Fig. 5(e).

the same procedure for the distribution of the time headways between a right lane vehicle with a short time headway, and its *follower* on the left lane [see a schematic representation in Fig. 5(d)]. The corresponding random procedure described in Fig. 5(e) is also performed.

Note that the random procedures in Figs. 5(c) and 5(e) are not completely equivalent. In order to compute the time headway as we define it, the ratio length/velocity of the leading vehicle has to be removed from the passage time difference in order to account for the size of the leading vehicle. In the random procedure of Fig. 5(c), this ratio refers to the predecessor on the left lane, while in the second case the ratio refers to the virtual vehicle. As a consequence, the distributions obtained from the random procedures in Figs. 6(a) and 6(b) differ slightly.

The conclusions, drawn from Fig. 6(b), are very similar to those for the forward case. Even more negative time headways are observed, i.e., vehicles on the right lane with a short time headway are more likely than others to have a very close follower on the other lane. When this occurs, they cannot overtake immediately, and their short headways are more likely related to the impossibility to overtake immediately rather than due to the preparation of an overtaking maneuver.

We checked also that, when a left-lane vehicle is partially side by side with a short headway right lane vehicle, the time headway with its follower on the same left lane follows a distribution which cannot be distinguished from the non biased intra lane time headway distribution (at least at the precision that can be reached from our data—statistics are less precise as this event does not occur so often). Anyhow this reinforces the observation that in general, the probability that a "hole" can be found to the left of right-lane vehicles with short headways is smaller than for "standard" vehicles.

Right-lane short headways thus seem to be related in many cases to steric constraints in the near neighborhood, and are thus likely to last at least until the local excess of density on the other lane is resorbed. The frustration yielding these short time headways could also favor potentially dangerous maneuvers, such as overtaking maneuvers with very short interlane time headways.

IV. CONCLUSION

The distributions of time headways between vehicles in different lanes have been measured, in order to characterize the environment of the right-lane vehicles which have a short time headway. We stress that the comparison of distributions that we did in Sec. III is valid only because we have selected a homogeneous traffic state. The obtained results rule out the idea that short time headways on the right lane could be only due to the preparation of passing maneuvers. Steric constraints can also induce short time headways—and these are expected to last for a longer time, implying some risk factor. In further investigations, we are trying to relate interlane velocity differences with the possibility or impossibility to pass due to steric constraints.

About intralane measurements, we show that pairs of vehicles separated by more than 6 other vehicles can exhibit strong velocity correlations and short time headways. This is certainly a security issue, as it is well known that the risk increases with the number of successive short time headways.

From the modeling point of view, note that strong non local correlations can be obtained with only nearest neighbor interactions. This is indeed the case with cellular automata, which exhibit strong—and most of the time pathological—nonlocal velocity correlations, in spite of purely nearest neighbor interactions. On the other hand, comparisons between car following experiments and models seem to show that, at least in some cases, vehicles do interact with multiple predecessors [14]. The conditions for multiple interactions—and the relevance of multiple interactions for modeling issues—still require investigations.

More generally, closely packed multilane microscopic structures still deserve observations and analysis in order to be better characterized and understood, in particular because of the crucial role that they play in security issues.

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