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Empirical Analysis of Lane Changing Behaviour at a Freeway Weaving Section

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Abstract

This paper presents an empirical analysis on lane changing behaviour using a trajectory data set collected at a weaving section in Grenoble (France). A detailed literature review shows that a strong empirical understanding of the weaving mechanisms is still lacking. This paper is devoted to fill this gap by investigating the lane changing behaviour at a microscopic level. We distinguished lane changes from the main road and those towards the main road. We conducted a descriptive empirical analysis of the weaving lane changes examining the positions of the lane changes and the accepted gaps. Our results show that under heavy congested traffic conditions the weaving vehicles tend to change lane as soon as possible after the start of the weaving section. When the traffic conditions are fluid, the lane changing positions are more spread along the first part of the weaving section. The weaving vehicles coming from the main road tend to change lane earlier than the weaving vehicles coming from the auxiliary lane. As the weaving vehicles change lane at the beginning of the studied weaving section, our findings ask whether the length of the weaving section is a key variable to estimate its capacity. Our findings raise also some questions about the more relevant micro-simulation models to reproduce the operation of weaving sections.

Keywords: weaving section, lane changing behaviour, microscopic empirical data.

Résumé

Ce papier présente une analyse empirique du comportement de changement de voie réalisée sur des données de trajectoires mesurées sur une zone d'entrecroisement à Grenoble (France). Une revue détaillée de la littérature montre que les mécanismes à l'œuvre sur les zones d'entrecroisement soulèvent encore de nombreuses interrogations. Ce papier vise à répondre à ces interrogations. Nous avons réalisé une analyse descriptive des changements de voie en considérant respectivement les changements de voie en direction de la bretelle et ceux en direction de la section courante. Nos résultats montrent que sous des conditions de trafic congestionnées les véhicules effectuent leurs manœuvres de changement de voie le plus tôt possible au début de la zone d'entrecroisement. Lorsque les conditions de trafic se fluidifient, les positions de changements de voie sont plus dispersées dans la première partie de la zone d'entrecroisement. Les véhicules se dirigeant vers la bretelle ont tendance à changer de voie plus tôt que les véhicules se dirigeant vers la section principale. Les résultats obtenus soulèvent des interrogations sur la pertinence de considérer la longueur de la zone d'entrecroisement comme un paramètre important pour en déterminer la capacité. Ils interrogent en outre la pertinence des modèles de simulation microscopiques couramment utilisés pour estimer le fonctionnement des zones d'entrecroisement.

Mots-clé: zone d'entrecroisement, comportement de changement de voie, données microscopiques.

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1. Introduction

Congestion on freeways mainly occurs at discontinuities of the road network such as merges and weaving sections. Merges have been intensively investigated from both empirical and simulation points of view. The most recent version of the Highway Capacity Manual (HCM, 2010) defines weaving sections as discontinuities of the road network formed when merge segments are closely followed by diverge segments. Because of their geometrical configuration, a lot of lane changes occur at weaving sections. Those lane changes lead to a reduction of the discharge flow, even if the total demand is lower than the capacity of the weaving section. As for many traffic phenomena, traffic in weaving sections has been examined either through data analysis, through deriving analytical expressions that permit to estimate level of capacities or through simulation.

Empirical analyses at a macroscopic level have been conducted in (Lee and Cassidy, 2009) and (Skabardonis and Kim, 2010) to identify bottleneck activation for two weaving sections. The authors used oblique cumulative vehicle counts from loop detectors placed inside the weaving zone at 400 m away (first site) or 500 m away (second site). From the oblique curves analysis, Lee and Cassidy (2009) conclude that “that bottleneck activations at both weaving sections were triggered by disruptive freeway to ramp lane changes”. They also explain that the location of the lane changes from the freeway to the ramp along the weaving section play a role in the discharge flow. To complete this overview of empirical data analysis, we need to mention (Sarvi et al., 2011) that presents a very small sample of microscopic data (130 weaving manoeuvres from ramp to freeway in total). Nevertheless, the authors conclude that “the surrounding freeway vehicles significantly affect the weaving vehicle acceleration behaviour”.

The operation at weaving sections is also estimated through analytical procedures. Lertworawanich and Elefteriadou (2003) used a combination of analytical formulas and a model of gap acceptance and linear optimization to forecast the capacity of weaving sections. The proposed methodology expresses the capacity as a function of the demands, the ratios of weaving vehicles and the speeds of weaving and non-weaving vehicles. A simple analytical model for estimating the capacity of weaving sections is proposed in (Rakha and Zhang, 2006). The model includes three variables: the weaving section length, the weaving section volume ratio and the weaving ratio. The paper also demonstrated that the proposed model is consistent with field data. Roess and Ulerio (2009a, 2009b) analysed very short periods, but for a set of locations representing a rather large variety of infrastructure characteristics. Those two papers present the updated methodology, integrated in the current version of the HCM 2010 (HCM, 2010), to design weaving sections. The first paper describes the first step of the methodology dealing with the estimation of the number of lane changes from and towards the freeway and the average speed of weaving and non-weaving vehicles (Roess and Ulerio, 2009a). The second paper aims at determining an analytical expression of a weaving segment capacity (Roess and Ulerio, 2009b). It is worth mentioning here that guidelines on weaving section differ from one country to another. For example, the Dutch guidelines for the design of weaving segments are compared with those of the U.S. HCM in (Minderhoud and Elefteriadou, 2003). The main difference is that the methodologies do not use the same variables to estimate the capacity. To summarize about guidelines for weaving section design and capacity estimation, one can say that they rely on the assumption that lane changing in weaving sections do have an impact on capacity but without a clear proof from empirical observations.

Simulation is widely used to estimate the capacity of weaving sections. The simulations can be conducted either at a microscopic level or at a macroscopic level. A review of previous studies and existing models about weaving section is proposed in (Shoraka and Che Puan, 2010). Simulation studies of weaving sections use existing models such as Simone (Calvert and Minderhoud, 2012) or Vissim (Roess et al., 2008). In this context, the capacity is expressed as the maximum rate of vehicles that are expected to traverse the weaving section. The capacity is a function of numerous factors such as the number of lanes, the length of the weaving section, the proportion of heavy vehicles, the length of deceleration and acceleration lane, the speed, etc. Existing models appear to not or hardly capture the specific traffic phenomena occurring at weaving sections. Therefore, some authors attempt to adapt existing models for the specific case of a weaving section. A generic continuous gas-kinetic traffic flow model is for example proposed in (Ngoduy, 2006) The lane changing probability is expressed as a function of the density, the speed, the weaving flow fraction and the vehicle compositions on the target lane. The proposed model is useful in supporting the geometry design for weaving sections by estimating their necessary length.

All previously mentioned papers agree on the conclusion that the fraction of lane changing vehicles, in relation to the total flow, strongly impacts the capacity of any weaving section. From that, design guidelines recommend long weaving sections. The underlying assumption is that, for a given proportion of lane changing vehicles, the longer the weaving section the higher the capacity, meaning that when the lane changes may be performed along a longer portion of road their impact is spread, lane changes may have separate and not a cumulative impact and the total capacity of the weaving section is higher.

However, the above presented literature review has illustrated that the longitudinal position of weaving lane changes is not sufficiently examined to confirm this assumption. The analysis of lane changing positions is also still lacking. In addition, the link between the road configuration and traffic flow characteristics and the longitudinal position, has not been investigated extensively. Therefore, this paper will examine the longitudinal position of lane changes using empirical observations of somewhat less than 1000 weaving manoeuvres. The data are trajectory data, collected through a helicopter.

The paper is organized as follows. A description of the data collection site and technique is given in the first section. Then, the methodology and the definitions to analyse the data are presented. The next section contains the results of the analysis, while the paper ends with conclusions and recommendations for future research.

2. Data collection site and technique

The weaving study site is shown in Fig. 1 (MOCoPo, 2011). It is situated at the junction between the urban freeways RN87 and A480 in the southeast part of Grenoble. We chose this weaving site because this junction is located in a dense urban network. The two traffic flows on this weaving section have different natures, competing for the same space:

- The medium distance traffic (few kilometers) corresponds to drivers using the RN87 and the A480 (either to the north – Exit 1- or the south direction – Exit 2) entering the weaving section in one of the two left lanes and exiting via one of the two rightmost exists;
- The local traffic originating from the rightmost entry lane and/or exiting on the left most lane.

The mix of traffic (local and medium distance), the total observable number of lane changes and the variety in lane changes at this weaving section allow us to have a combination of traffic situations reflecting various mechanisms of occurrence of congestion.

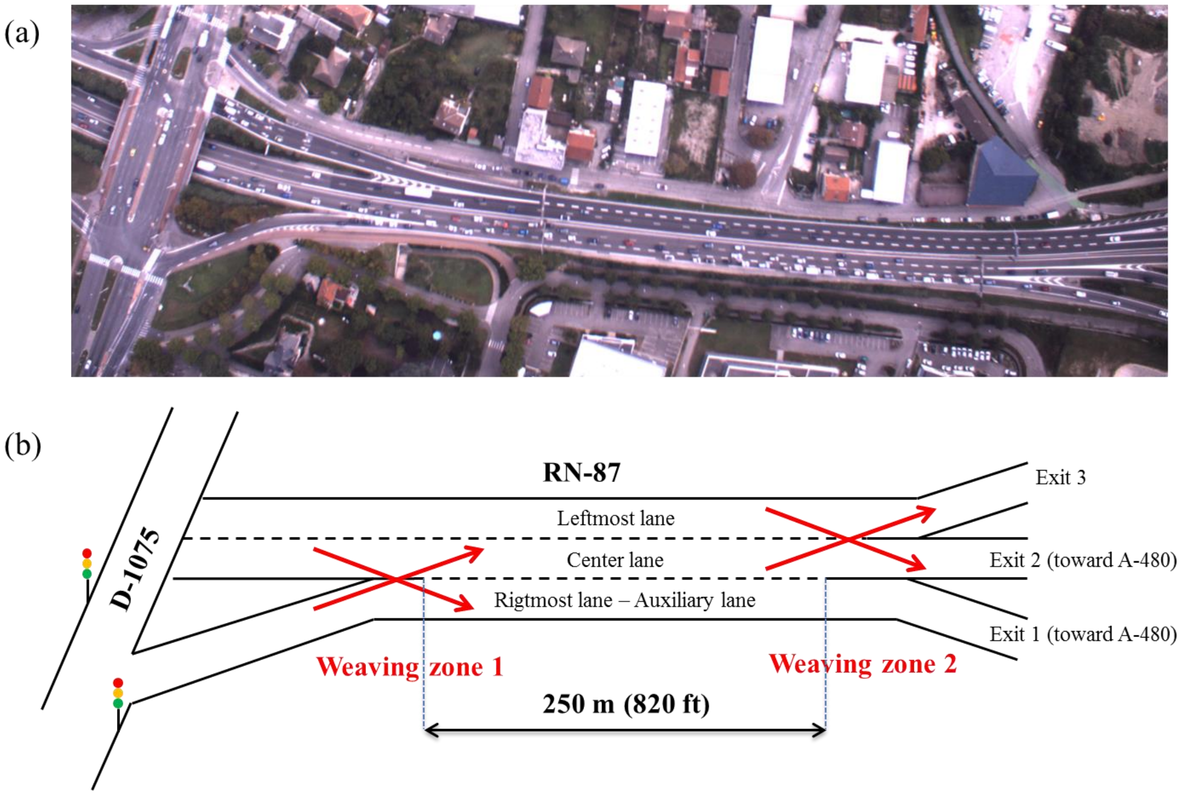

Fig. 1. (a) aerial view of the site; (b) sketch of the site

The weaving section consists of two lanes on the main road and one auxiliary lane. The maximum allowed speed on the main road is 70 km/h (20 m/s). The block marking between the main road and the auxiliary lane has a length of 250 m. The arrival pattern at the auxiliary lane is specific to the studied weaving section. A traffic signal, just upstream of the auxiliary lane, creates platoons of vehicles. Note that the infrastructure configuration is not simply a 2+1 -> 2+1 weaving classical type A configuration, but more a double type A weaving section with two entries and three exits. The analysis described in the paper focusses on the weaving zone n°1.

The video recordings have been collected using a high-resolution video camera mounted underneath a helicopter. For a further explanation of the procedure to stabilize the images and extract the trajectories, the authors redirect their readers to (Knoppers et al., 2012). The weather conditions were dry and sunny.
We consider in this paper two one-hour samples respectively recorded on Thursday, September 15th 2011 and Friday, September 16th 2011. The traffic during these two hours is either in free-flow or in congestion with prevalence of congestion. The congestion forms downstream of the weaving section at Exit 1 or Exit 2 (see Fig. 1). Then, the congestion moves upstream on both the main road and the auxiliary lane. There are also some periods for which the studied weaving section is an active bottleneck. The congestion forms at the start of the weaving section and moves upstream on the centre lane and the auxiliary lane.

The traffic mainly consists of passenger cars. The quality of the data is, at the time we write this paper, not good enough to have a complete trajectory for every vehicle passing the weaving section. We propose in this paper a descriptive analysis of the lane changing behaviour. Therefore, we only need big enough samples to have statistically significant results.

We selected from the datasets, the weaving vehicles for which we have a complete trajectory, as well as the complete trajectories of their putative leader and follower on the target lane. This results in the following samples:

- 544 lane changing trajectories from the auxiliary lane to the main road and 995 lane changing trajectories from the main road to the auxiliary lane for Thursday, September 15th 2011;
- 450 lane changing trajectories from the auxiliary lane to the main road and 705 lane changing trajectories from the main road to the auxiliary lane for Friday, September 16th 2011.

3. Methodology and definitions

Fig. 2 presents the conceptual framework describing the weaving behaviour based on a previous work on merging behaviour (Marczak et al., 2013). In this model, the input of the decision to change lane consists of the offered gaps, the weaving section configuration and the characteristics of the drivers. The output of the decision to change lane are the accepted and the rejected gaps. The offered gaps are a result of the traffic conditions on the weaving section, the characteristics of the vehicles composing the gap on the target lane (acceleration, speed, length of the vehicles) and the previous lane changing manoeuvres. The interactions at weaving sections are very complex due to the involvement of weaving and non-weaving flows in the mandatory lane changing process. One of the objectives of this paper is to get insights of these interactions between weaving vehicles.

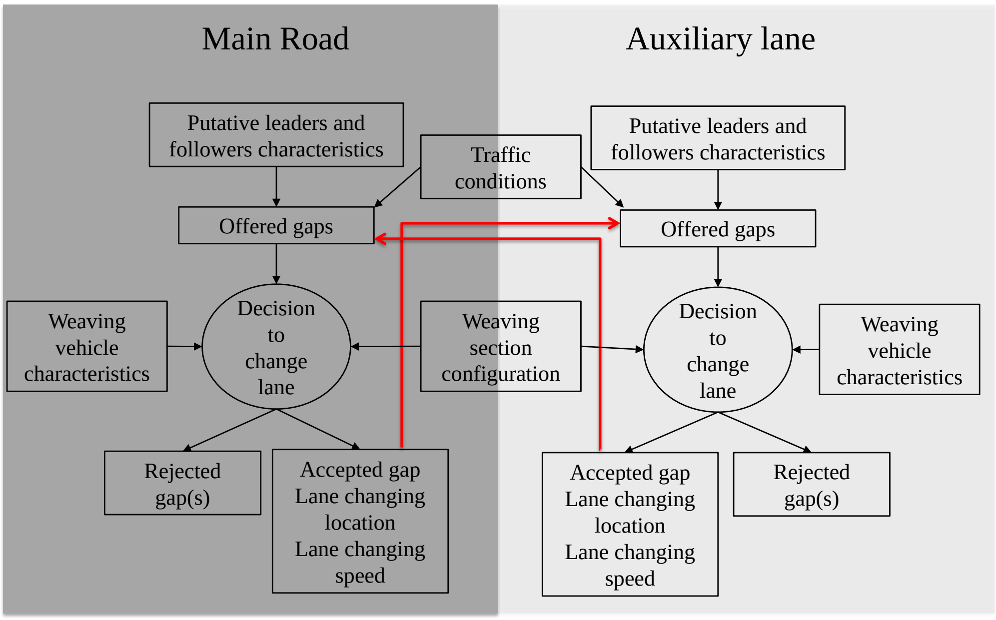

Fig. 2. Conceptual framework to study lane changing behaviour at weaving section

In the remainder of this paper, we focus the analyses on the results of the decision to change lane. We consider the lane changing positions, the lane changing speeds and the accepted gaps as key variables to explain the lane changing behaviour.

In the two one-hour video datasets considered in this work, the congestion mainly occurs because of the interaction between the lane changing vehicles coming from the centre lane and those coming from the auxiliary lane (weaving zone 1 in Fig. 1). The lane changing vehicles reduce their speed (i) to find a gap and change lane or (ii) to let a vehicle coming from the adjacent lane perform its lane changing manoeuvre. As they are part of the mechanism that causes the congestion, we distinguish two types of mandatory lane changes: (i) the lane changes from the rightmost lane on the main road to the auxiliary lane and (ii) the lane changes from the auxiliary lane to the main road. We call “main road weaving vehicle” a vehicle coming from the main road and changing lane to reach the auxiliary lane. We define inversely a “ramp weaving vehicle” as a vehicle coming from the auxiliary lane and changing lane to reach the main road.

We define the lane changing moment as the moment that the centerline of the weaving vehicle crosses the block marking between the main road and the auxiliary lane. The accepted gap is the net distance between the putative leader and the putative follower at the lane changing moment. The speed of the weaving vehicle at this moment is defined as the lane changing speed. A weaving vehicle could not change lane at a high speed if the traffic conditions on the target lane are congested. The longitudinal position of the weaving vehicle at the lane changing moment is defined as the lane changing position. It is measured from the start of the block markings. One of the objectives of the paper is to assess whether there is an interaction between lane changes of the different weaving flows. To this aim we consider the lane changing positions. We assume that if there are interactions between weaving vehicles, a correlation should exist between the lane changing positions.

4. Results

We aim at determining whether a relation exists between the lane changing position of main road weaving vehicles and the lane changing position of ramp weaving vehicles. We start therefore the empirical analyses by considering the lane changing position. Fig. 3 shows the cumulative distributions of the lane changing positions of both vehicle groups on both days.

As traffic conditions during observations were essentially congested, not many observations can be found when the speed is bounded by 15 m/s and 20 m/s. Approximately 25% of the lane changes occur before the start of the block markings when the traffic conditions are very congested (speed below 5 m/s). The analysis of the video recordings shows that this situation occurs when the congestion comes from downstream (from Exit 1) and moves upstream on the centre lane and the auxiliary lane (see Fig. 1). When the traffic conditions are very saturated drivers, independently of their direction, tend to change lane as soon as possible to reach their target lane. When the speed is below 10 m/s, the lane change locations are spread out along the block marking. In this case, more than 95% of the lane changes occur in the first 150 m of the weaving section. So even then, not the total length of the weaving section is used.

The cumulative distributions for the lane changes of the main road weaving vehicles and the ramp weaving vehicles are very similar. It appears however that the lane changes towards the auxiliary lane occur, in general, earlier than the lane changes in the other direction when the speed becomes higher than 5 m/s. Because of the specific arrival pattern at the auxiliary lane, there are occasionally fewer vehicles on this lane. The vehicles coming from the main road towards the auxiliary lane can find larger gaps to change lane. Those observations are similar for both days.

To test whether or not two datasets are from the same distribution, one classical way is to use a Kolmogorov-Smirnov test to assess if the null hypothesis (the two datasets are from the same distribution) is accepted or not. We chose this method to evaluate first, if for each day the distributions of the lane changing positions for the two directions are similar, second if the distributions for one direction inside a speed class are similar. At a 5% significance level, the null hypothesis is always rejected. One can thus first of all conclude that there is, for a given day, a significant difference between the lane change locations for the two different directions. The second conclusion is that the distributions for one direction are also different from one day to another.

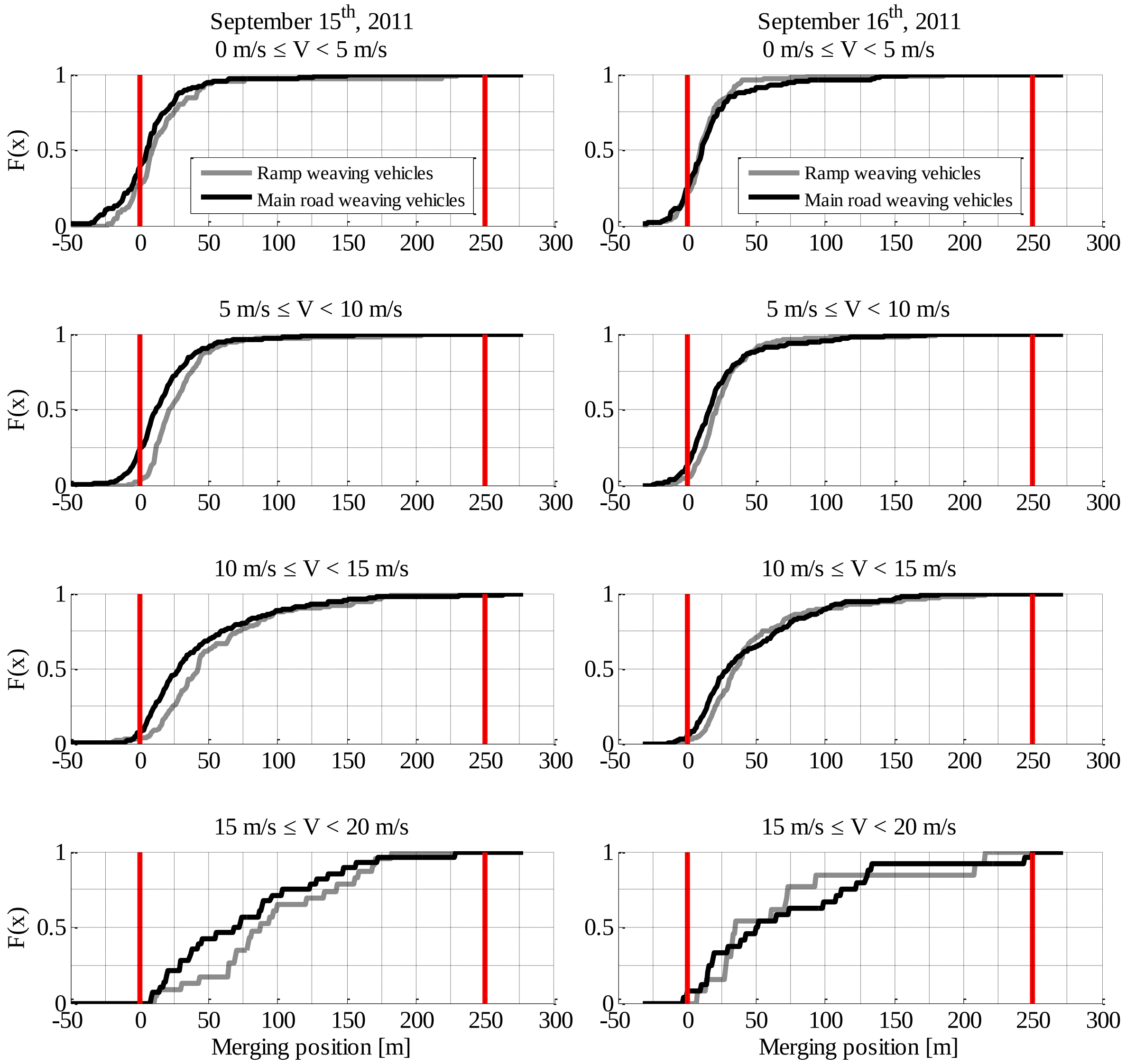

Fig. 3. Cumulative distributions for lane changes positions for different classes of speed. We consider the lane changes of main road weaving vehicles (black line) and the lane changes of ramp weaving vehicles (grey line).

The next analyses deal with a cross-comparison of the lane changing positions and the speed to determine whether a relation between the lane changing positions, in relation to the prevailing traffic conditions, exists or not. Fig. 4 shows the mean value of the lane changing positions from the main road as a function of the lane changing positions towards the main road. The data have been aggregated using the lane changing speed. The confidence intervals at the 5% significance level are also represented. The colour of the dots gives the speed: the darker the dot, the lower the speed.

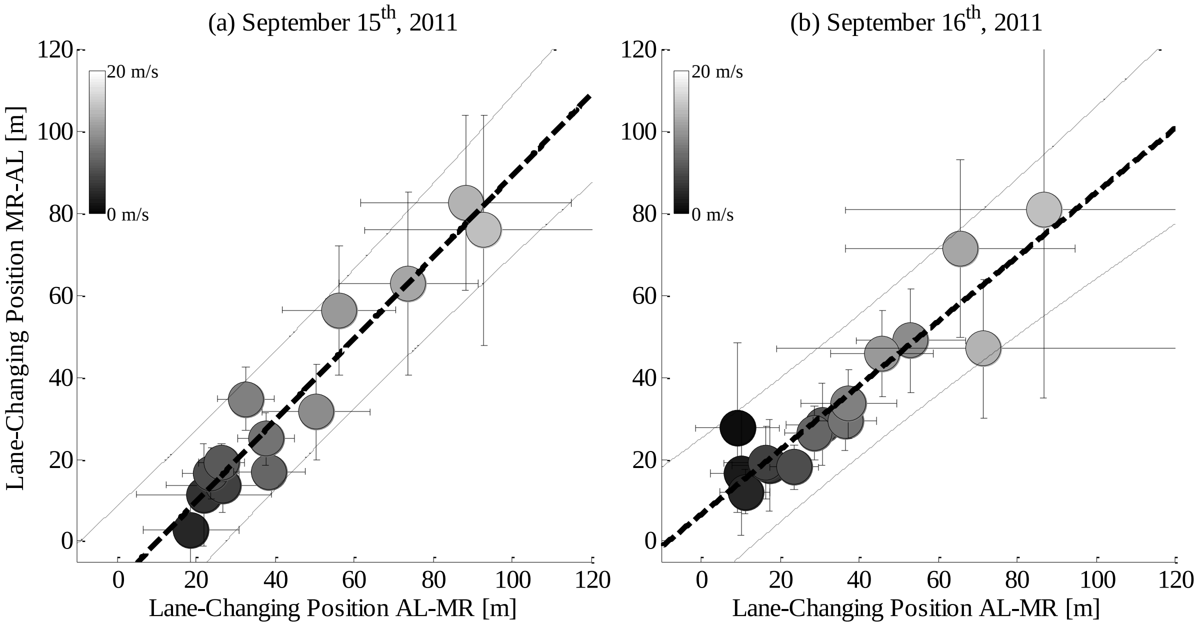

Fig. 4. Mean lane changing positions for main road weaving vehicles as a function of the mean lane-changing positions for ramp weaving vehicles. The colour of the dot gives an indication of the speed of the weaving vehicle at the time of the lane change: the darker the dot, the lower the speed.

Fig. 4 shows that there seems to be a relation between the lane changing positions in both directions. The linear regression lines that fit the data for September, 15th and September, 16th are respectively

$$x_{MR\text{-}AL} = 0.99\, x_{AL\text{-}MR} - 10.36 \qquad (R^2 = 0.92;\ PCC = 0.96) \qquad (1)$$

$$x_{MR\text{-}AL} = 0.78\, x_{AL\text{-}MR} + 6.46 \qquad (R^2 = 0.86;\ PCC = 0.93) \qquad (2)$$

$x_{MR\text{-}AL}$ (resp. $x_{AL\text{-}MR}$) is the lane changing position for the main road weaving vehicles (resp. the ramp weaving vehicles). The coefficient R^2 equals the square of the Pearson correlation coefficient (PCC) that is a measure of the linear correlation between two variables. The PCC is higher than 0.51, the threshold at a 5% significance level for 13 degrees of freedom (15 observations – 2). One can therefore conclude that there is indeed a linear correlation between the lane changes from and towards the main road for the prevailing traffic conditions.

Previously, the data have been aggregated using the speed. This gives an insight into the relation between the lane changes from and towards the main road for the prevailing traffic conditions. However, it does not illustrate a temporal relation between the lane changes. We assume that the lane changes at a weaving section are the results of a collaboration/competition between the weaving vehicles. If this assumption is true, the lane changes for a given time period should occur at the same location.

The confidence intervals for each speed class overlap. Fig. 5 shows therefore that the mean lane changing position for the lane changes from the main road is not significantly different from the mean lane changing position towards the main road. Fig. 5 confirms that, for a given time period, the lane changes occur at the same location. Fig. 5 also shows that the temporal mean lane changing position is constant with the time.

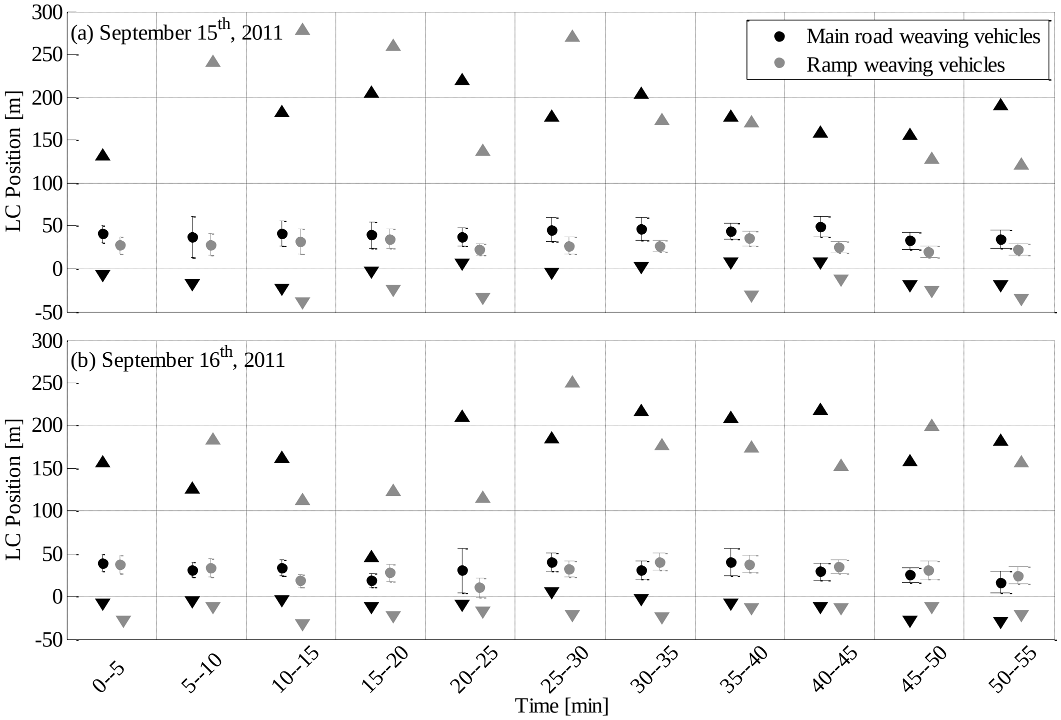

Fig. 5. Temporal aggregation of the lane changing positions: the mean temporal lane changing positions and their corresponding confidence intervals at à 5% significance level are represented. The upward-pointing triangles represent the maximum observed lane changing position. The downward-pointing triangles represent the minimum observed lane changing position.

The empirical analyses continue with an analysis of the accepted gaps, see Fig. 6. Hereafter, we focus on the accepted gaps. Our findings show that the weaving vehicles change lane at the start of the weaving section. The choice process seems very simple: the drivers take the immediate neighbouring gap. Fig. 6 shows that the ramp weaving vehicles accept smaller gaps than the main road weaving vehicles. Only the largest accepted gaps are similar for both types of lane changes. The pattern is similar for both days. The specific arrival pattern on the auxiliary lane could explain those observations. The main road weaving vehicles accept larger gaps because temporarily fewer vehicles are driving on the auxiliary lane when the traffic light is red. So basically, the difference is not in their choice process, but in the offered gaps, which are simply larger (on average).

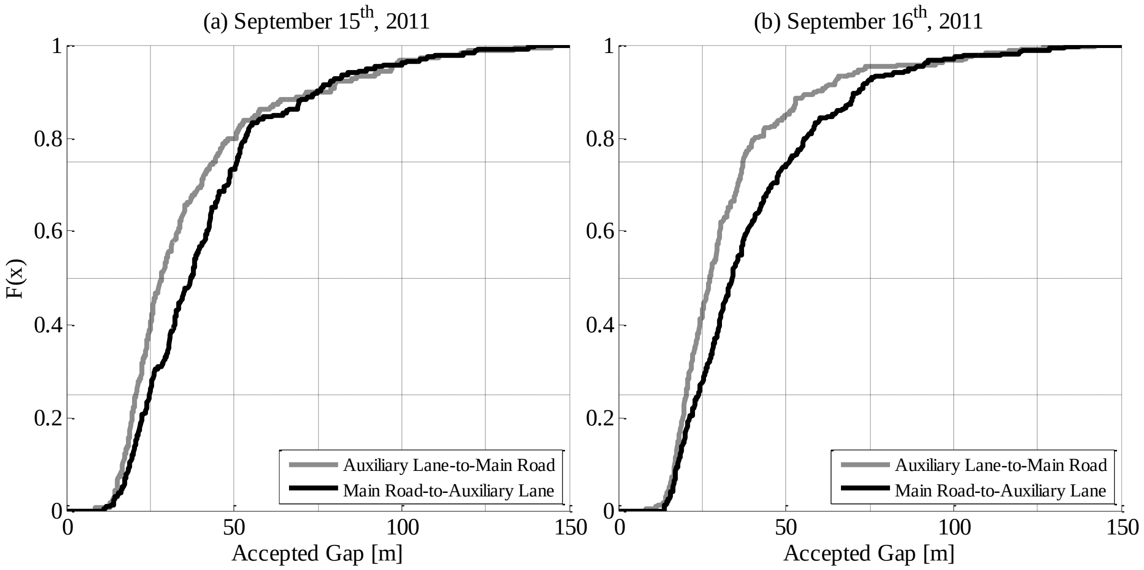

Fig. 6. Cumulative distribution for accepted gaps

5. Discussion and conclusion

A descriptive analysis of the lane changing behaviour using trajectory data measured at a weaving section is presented in this paper. This work is the first part of a larger research project about weaving sections. The aim of this analysis is twofold. We analyse the trajectories at a microscopic level to better understand the mechanisms that occur at a weaving section (especially the lane changes). The empirical analysis will be also useful to develop/improve and validate accurate models to estimate the capacity of weaving section. We analysed the longitudinal lane changing positions and the accepted gaps to determine whether a relation exists between the lane changes from and towards the main road.

The trajectories have been collected using a high-resolution camera mounted underneath a helicopter. The studied weaving section is located in Grenoble (France). We do not have sufficiently accurate data to be able to analyse the lane changing activity in the whole weaving section. In particular, we are not able to study the acceleration of the weaving vehicles. However, we can give first insights into the lane changing behaviour at a weaving section.

The main findings of the paper are the following:

- The analysis of the longitudinal position shows that the lane changes occur in the first part of the weaving section, even before the start of the block line, when the congestion is heavy.
- When the traffic conditions are very congested the lane changes from and towards the main road occur at the same location near the beginning of the weaving section;
- With increasing speed, the lane changing positions are more spread out along the block line between the main road and the auxiliary lane. Under free-flow conditions, more than 95% of the lane changes occur in the first 150 m of the weaving section. The first 60% of the total length of the weaving section are used to change lane;
- With increasing speed, the weaving vehicles coming from the main road change lane earlier than the weaving vehicles coming from the auxiliary lane;
- There is a linear correlation between the lane changes from and towards the main road. One can therefore reasonably assume that the weaving vehicles interact in a competition/collaboration behavior especially when the traffic conditions deteriorate;
- The vehicles changing lane from the auxiliary lane to the main road accept smaller gaps and headways than the vehicles changing lane from the main road to the auxiliary lane.

Previous studies using micro-simulation to estimate the capacity of a weaving section pinpointed that the length of the weaving section is a key factor influencing its capacity. However, our empirical study shows that only 60% of the total length of the weaving section is used to change lane. This length reduces in case congestion occurs.

Recent studies considered the gap acceptance theory to model the lane changes at a weaving section. Our empirical observations raise the question whether the gap acceptance theory is the most appropriate theory to reproduce the lane changing behavior at a weaving section. In our view the lane changes at a weaving section are more the results of a competition/collaboration between the weaving vehicles. This will be subject for future research.

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