An Empirical Study of Lane-Changing Maneuvers in a Weaving Area Based on Reconstructed Trajectories of Floating Car Data

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ABSTRACT:

The concentration of lane-changing maneuvers is the main contributor to speed drop and congestion in weaving areas. Despite their importance, lateral maneuvers have received less attention in research than longitudinal driver behavior. The main reason for this is the lack of appropriate data for comprehensive analysis. In this paper, we have used reconstructed lane-level accurate trajectories collected during 12 days in a weaving section with a length of more than 3.3 kilometers. Examining the classification of maneuvers into mandatory and discretionary versus their classification based on the direction of the maneuver showed that the latter could be better described by traffic variables such as changes in density and speed of the target lane compared to the source lane. We have also shown that the origin-destination pattern of drivers and the time of day (traffic conditions at different hours) have a significant effect on the number and location of lane change maneuvers. In addition, the location of performing the weaving maneuvers at different times of the day appears to affect the travel time experienced by drivers. This data source and in-depth analysis open many opportunities for improving empirical traffic flow theory, better design of weaving sections, and active management through V2X communication and online drivers' guidance toward cooperative behavior.

Keywords: Empirical traffic analysis, Lane changing maneuvers, Lateral driving behavior, Motorway weaving areas.

INTRODUCTION

A lane-changing maneuver (LCM) is associated with occupying two lanes by a single vehicle during the maneuver. This phenomenon leads to capacity and speed drop, as well as a decline in traffic safety. As these maneuvers are more frequent in complex motorway segments such as weaving areas, these areas are more prone to capacity drop and congestion spillback. Furthermore, since LCMs often require a gap acceptance decision, this maneuver is correlated to an increased risk of traffic accidents.

On the other hand, and from a salient practical aspect emerging connected and automated vehicles opened an avenue of opportunities to enhance the traffic flow quality based on real-time guided and cooperative management strategies. An in-depth empirical analysis of LCMs might reveal when, where, and under which traffic circumstances drivers may perform their LCMs, therefore assisting the researcher in understanding and modeling these choices and understanding the correlation between LCMs and congestion formation, reduced congestion discharge (capacity drop), and accidents. More effective and efficient management strategies might be devised based upon well-defined hypotheses derived from such a deeper understanding. Furthermore, whereas microsimulation software contributes significantly to traffic flow study, an uncalibrated simulation has nothing to tell and might possibly mislead the whole investigation. Although there is a significant amount of research on the calibration of these microsimulators, the effort for software calibration for lateral movements (when, where, and under what traffic circumstances) has so far been largely overlooked. A comprehensive empirical study may facilitate this exploration as well. And last but not least, one would not be able to well-developed an LCM prediction model without a comprehensive understanding of why LCMs perform and the associated descriptive variables. Such recognition is possible only through insights that a researcher might gain from empirical analysis. These are satisfactory reasons to consider lane-change and lateral maneuver studies indispensable research topics.

In spite of its significance, there is surprisingly little research on lateral vehicle movements in the published literature. The main reason for this research gap is the lack of proper empirical datasets: e.g., continuous vehicle trajectories in time and space (with sufficient lateral accuracy). Although several efforts have emerged for trajectory data collection in the past decade, they all suffer from one or more of the following shortcomings. The vast majority of them are severely restricted in terms of duration and/or road coverage length, and those that are not, are pretty expensive. Another source is the high-precision reconstructed trajectories that are preliminarily collected by cellphones. However, such data is not accessible to the public.

This research, therefore, offers an empirical investigation of LCMs in a weaving region on the Belgian highway network around Antwerp, based on such time and space continuous reconstructed trajectories. The study conducted an extensive study network that includes a crucial weaving area and is well-known in the country road network as a highly congested segment. We present a comprehensive exploration that takes into account several variables such as origin-destination (OD) pattern of vehicles, time of day, density, speed, and travel time.

The main objectives of this research are bi-folded; on one side, we intend to demonstrate the capability and features of the new generation of reconstructed trajectories of low-precision GPS of smartphones and floating car data in the detailed empirical analysis of traffic flow. On the other side, we tried to cast a light on the LCM behavior in a complex, lengthy motorway segment based on data collected over several days. Along with studying the effect of traffic characteristics on the LCMs that received attention in past studies, we aimed to explore how drivers distribute their maneuvers in time and section length during peak and off-peak periods.

The remainder of the paper is structured as follows: In Section 2, a literature review on empirical analysis of weaving areas and lane changes is discussed briefly. Then the study network and data collection are presented. The fourth section belongs to an in-depth empirical analysis of LCMs. And finally, we bolded remarks and concluded the paper in the last section.

LITERATURE REVIEW

One of the earliest empirical analyses of LCMs was done by Worrall et al. The study includes data from 30 freeway locations in Chicago and is conducted from a macroscopic viewpoint. They concluded that the average lane-changing frequency is increasing by rising average flow speed (1). Since then, several studies have explored the characteristics of LCMs, such as their frequency, distribution along the road, duration, acceleration/deceleration pattern, etcetera. Moreover, the relationship between LCMs and traffic characteristics such as density and speed were investigated.

In the analysis of the location of performing LCMs, Bham concluded that the majority of both drivers wanted to merge through an on-ramp (76%) and those who intended to diverge through an off-ramp (74%) performing their maneuvers in the first 91.4 meters (300 feet) of the weaving area (2). In a separate study, the authors reached the same results and concluded that the concentration of LCMs close to the entry gore makes this zone prone to a higher frequency of traffic accidents (3). van Beinum et al. examined the location of the weaving maneuver concerning the entry gore and concluded that the lower the flow-to-capacity ratio, the higher percentage of early weavers (4). Daamen et al. reported that the merging location is a function of the congestion level. They find out that during the off-peak, early weaving behavior is dominated, and it is vice versa during the peak period (5). Ahmet et al. claimed the drivers' location choice of their weaving maneuver is a function of the degree of perceived risk associated with the maneuver and available gaps (6). Zhang et al. concluded that the choice of LCM location for merging vehicles is a compromise between trying to move toward their destination and improving their driving condition, and in higher traffic density, the second factor is more significant (7). Ahmed et al. concluded that most of the weaver drivers that join from an on-ramp to the mainstream perform their mandatory maneuvers as soon as possible (8). In another study, authors revealed a high tendency for LCM towards right among the drivers who continue in the mainstream right after an off-ramp (9).

Toledo and Zohar analyzed the duration of LCMs and concluded that whereas the average range of LCM duration is 5 to 6 seconds, this period is longer during the peak period compared to the off-peak, and the direction of the maneuver has not had a meaningful effect on maneuver duration (10). Another study has tried to provide the best survival function for the LCMs duration (11). Moridpour et al. reported that LCM duration is shorter for passenger cars than for heavy vehicles and negatively correlates with vehicle speed (12). It was claimed that LCM duration has a significant inverse relationship with vehicle speed and acceleration (13).

Knoop et al. showed that increases in the density of source and/or target lanes are always associated with increasing the number of observed LCMs. They showed that in the majority of the cases, maneuvers toward the right lead to speed loss, and maneuvers toward the left lead to speed gain (14). On the contrary, Match et al. argued that LCMs are increasing up to traffic density values around 12 to 15 and decreasing for densities higher than that for maneuvers toward the right and left. However, the LCM duration is always increasing by rises in density for maneuvers to each of both sides (15). It also concluded LCM rate decreases as the traffic density increases (16). The driver’s justification regarding the density and speed of the target lane versus other alternative lanes revealed that in most cases, maneuvers towards the left are associated with speed gain, and maneuvers towards the right are associated with speed loss. In contrast, such a clear conclusion cannot be made regarding density differences (17).

In this paper, we used reconstructed trajectories from low-precision smartphone GPS of floating car data instead of conventional video-based trajectories for lane-change studies. In the currently available studies discussing reconstructed trajectories, either the trajectories were not at a lane-level accuracy and thus not suitable for lane change studies or were about reconstructing missing parts or inaccuracies in video-based trajectories. To use this new generation of trajectory data in this paper, we defined criteria to distinguish between mandatory and discretionary maneuvers. A descriptive analysis, along with several spatio-temporal distributions, are used to empirically characterize the LCM behavior in some aspects that have hardly been analyzed so far because of the limitation of the conventional video-based trajectory data. In comparison with the existing literature, all available studies have examined LCMs in many different directions, but this paper's most significant contribution can be summarized as follows:

- For the first time, this research proves the practicability of trajectories reconstructed from floating car data against video-recorded ones. We can reconstruct as many trajectories as required to passively monitor traffic phenomena for several days and over an extended road network of approximately 3.3 Km.
- We found that drivers' LCM is a function of traffic parameters (density and speed), maneuver intention (mandated versus discretionary), and maneuver direction. The results might be reused as a starting point for model estimation and calibration of available models and microsimulation software.
- This paper shows that, contrary to popular belief, all discretionary LC maneuvers are not oriented to easier driving. Rather, some are anticipating behavior, and although they immediately lead the driver to a slower lane, they avoid getting tackled in a queue downstream.
- For the very first time, we explored the influence of where weaver drivers conduct their mandatory LCM on their travel time inside the weaving area.

TEST NETWORK AND DATA COLLECTION

A weaving area in the R1 inner motorway ring near Antwerp, Belgium, serves as the test network for this paper. Users of the Touring Mobilis and Flitsmeister smartphone apps (available for iOS and Android) of commercial traffic service company Be-Mobile were observed passively for the data collection. This weaving area is a part of a more extensive highway network between interchanges Antwerpen-Oost and Antwerpen-Zuid (**Figure 1**). A geofence was defined around the weaving section. As soon as a smartphone app user enters the geofence, the vehicle position is automatically recorded at a 1 Hz frequency. The smartphone application transmits trajectory data online to the Be-Mobile server, where it is accessible for study by the research team a few hours later. Trajectory information comprises a dedicated unique ID for each vehicle (smartphone) and a timestamp based on local time (Central European Time (CET)) and vehicle spatial position, including latitude and longitude in the WSG84 coordinate system (EPSG: 4326), in addition to speed and heading. Vehicles do not need to be equipped with any extra device nor did drivers receive any driving instructions since they are entirely anonymous and ignorant of our observations (apart from their mandatory consent (required by law) upon installation of the app that data would be collected). As a consequence, drivers make their own decisions about driving lanes and maneuvers like lane-changing and overtaking without being influenced by passive monitoring.

Being registered by smartphone GPS, the lateral position accuracy is insufficient to locate the vehicles on lanes, hence, to identify lane changes. To remedy this, the GPS data was fused with individual vehicle passage data registered by lane-specific loops, based on correspondence of passage time, speed and consistency of vehicle length – see for further details on this fusion method (18). This fusion corrects the lateral position to errors less than the width of a standard lane in motorway networks, so that the driving lane can be identified and lane changes can be located on a lane-specific digital map that was estimated from the raw trajectories (19). The reconstructed trajectories used in this study have two main advantages compared to the conventional trajectories collected based on video recording and image processing. First, the reconstructed trajectories are continuous and much broader regarding the time of data collection and the length of trajectories/network. Second, given the ongoing amassment of smartphone trajectories by the app and loop detector data, the researcher can decide to reconstruct trajectories based on any specific observation passively.

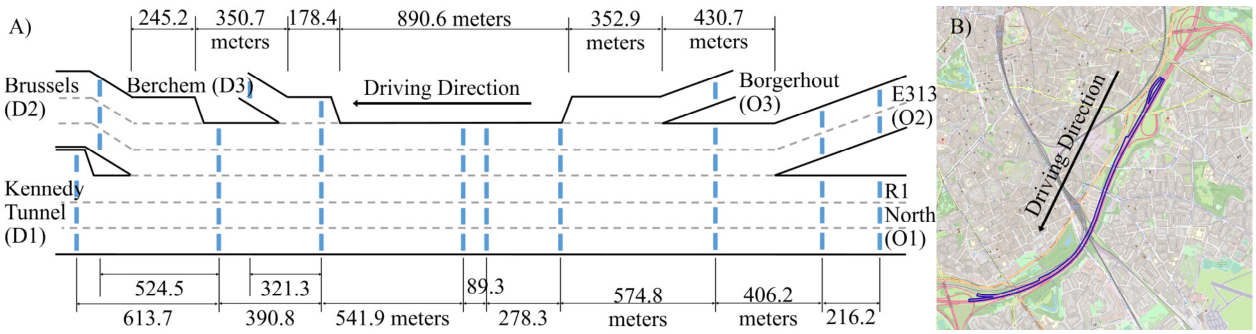

Figure 1 A) An abstract sketch of the weaving area (total length of 3.3 Km), the blue rectangles representing the loop detectors, and the flow direction is right to left. B) Location of the weaving area inside the motorway network around Antwerp

The weaving area under study carries high traffic volumes of more than 125,000 per day. Moreover, the traffic flow in this weaving area is highly heterogeneous in terms of the familiarity of drivers by network and the combination of commercial trucks and passenger cars, among others, because of its proximity to the port of Antwerp. For the analysis purpose of this paper, we used the trajectories collected during 12 working days in September and October 2019, after the start of the new academic year of schools and universities. Whereas the traffic state patterns on all these days are not exactly the same, in selecting these days, three criteria have been considered: 1) all the loop detectors inside the network needed for the data fusion with the GPS data should be working properly and collecting data between 5:00 and 21:00 , 2) no traffic accident should have happened inside the weaving area or its vicinity, and 3) the weather condition should be normal (no snow, heavy rain, fog or road surface freezing).

As illustrated in **Figure 1**, the weaving area consists of three origins (O1 mainstream, O2 major on-ramp from interchange Antwerpen-Oost, and O3 minor on-ramp) and three destinations (D1 mainstream, D2 major off-ramp towards interchange Antwerpen-Zuid, and D3 minor off-ramp). On average, the penetration rate of collected and reconstructed trajectories is between 1% and 2%. However, the sample is not balanced on the nine pairs of OD-flows and at different hours of the day. In total, 14,432 trajectories have been investigated for the analysis purpose of this paper. The generalized OD matrix has been computed by the Furness method (doubly constrained growth factors method (20), with the constraints provided by the detector counts at each O and D) on an hourly basis after initialization with the number of observed trajectories. The generalized OD matrix, as well as the generalization factors, are presented in **Table 1**. As Borgerhout on-ramp (O3) and Berchem off-ramp (D3) are mainly serving as parts of the local network, and it seems drivers are less likely to use the tracked navigation apps for local trips, the penetration rate for trajectories originated and/or destinated from/toward these ramps are so low, and hence they have been excluded from further investigation.

Table 1 Daily traffic flow and generalization factors of trajectories based on the origin and destination inside the weaving area (numbers in parentheses are standard deviations; bold numbers are the weaving flows)

	Average Generalized Daily OD Matrix			Average Generalization Factors		
	Kennedy Tunnel (D1)	Brussels (D2)	Berchem (D3)	Kennedy Tunnel (D1)	Brussels (D2)	Berchem (D3)
R1 North	23,414	**35,968**	7,124	59.2	77.1	335.5
(O1)	(3,524.2)	(9,458.4)	(1,019.5)	(9.9)	(17.4)	(42.2)
E313 (O2)	**25,128**	17,411	5,458	129.8	109.6	887.8
	(1,009.7)	(3,219.5)	(1,447.3)	(8.8)	(9.4)	(115.4)
Borgerhout	5,168	6,431	1,842	1,319.2	1,346.1	1,802.8
(O3)	(2,288.4)	(2,225.2)	(2,302.7)	(505.4)	(477.5)	(592.7)

EMPIRICAL ANALYSIS OF LANE-CHANGING MANEUVERS

Given the time series of longitudinal and lateral coordinates in the reconstructed trajectory for an anonymous vehicle ID and the digital map of the lane markings for the study network as discussed in the previous section, it is straightforward to identify the driving lane of the vehicle at each timestamp (second). Anytime a vehicle exceeds the line between two lanes, we infer that an LCM occurs. However, there are two exceptional situations. In these situations, an actual LCMs does not accomplish; rather, it only appears to be: 1) When a vehicle drifted narrowly into the adjacent lane (in most instances, less than a meter), which may either be an artifact of the lateral position error after reconstruction (that was reduced significantly but not eliminated completely (18)), or may be an unintended line crossing due to a misconduct in steering control. 2) When entering the adjacent lane and returning to the source lane, both were fulfilled during a brief time period. Such a case may appear to be an overtaking, but given the minimum duration of on average 3 seconds required for a lane change (10, 11) and for surpassing another vehicle, lane crossings that, combined, span less than 8 seconds will not be considered actual overtaking.

In total, the generalized traffic flow entering the weaving from O1 and O2 and the number of their corresponding LCMs in 12 selected days are 1,223,050 and 2,638,199 (average penetration rate of 1.18%), respectively, equivalent to 2.51 (StDev = 0.42) and 0.86 (StDev = 0.23) LCMs/Veh for the weaver drivers and non-weaver drivers, respectively. These rates for the weaver and non-weaver drivers of the weaving area of NGSIM data (US-101) are reported as 1.6 and 0.28, respectively (6). two other studies in weaving areas in California and Baltimore mentioned 0.89 (2) and 1.97 (3) as the LCM rates for the weaver drivers, respectively. Almost 60% of this total traffic flow are weavers (O1→D2 or O2→D1); however, they are responsible for 75.5% of all LCMs in the study area, and 39.4% of all performed LCMs are mandatory maneuvers. A mandatory LCM is defined as a maneuver that a driver should conduct in order to reach her/his destination (21-23). Two key elements in this definition are the necessity of the driver to accomplish the maneuver and the presence of a specific direction (lane or lanes) that the driver must reach. So, in this paper, four criteria must be met in order to consider an LCM mandatory: 1) only weaver drivers may perform a mandatory maneuver, 2) let us call the lanes that end directly at the ramp (L3'-L5) or mainstream (L1-L3) as the destination lane group. Then the maneuver should be toward the destination lane group, 3) the maneuver should not be followed by another maneuver in the opposite direction compared to the destination lane group and 4) the target lane should not exceed the first lane of the destination lane group. **Figure 2** is utilized to illustrate this definition. LCMs are bolded with red markers; when LCMs number 1 and 4 are mandatory, the rest of this vehicle's maneuvers are considered discretionary maneuvers.

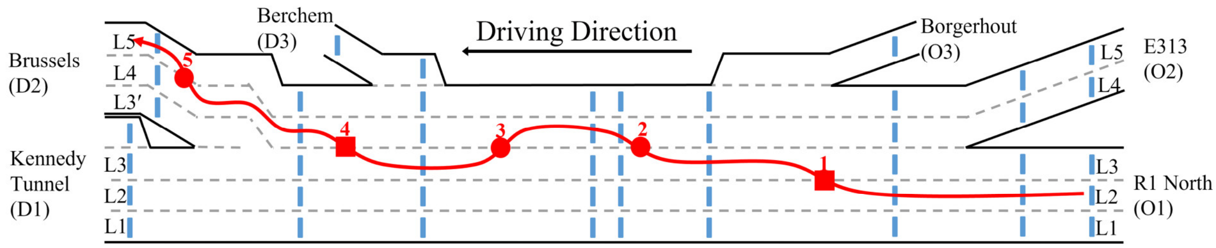

Figure 2 Mandatory (1, 4 red squares) versus discretionary maneuvers (2, 3, 5 red circles), the flow direction is right to left.

Except for two short segments that are auxiliary lanes of O3 and D3, the whole study area could be considered a 5-lane highway network. Whereas traffic states on selected days are not exactly the same, **Figure 3** could be considered a representative for selected days. This figure illustrates the lane-based speed estimation of traffic flow. Lane numbers are increasing from left to right. Three prominent traffic patterns are notable in this figure. 1) The morning peak period (6:30-9:30) when the speed drop started around the last loop detector station before the divergence of D1 and D2. This speed drop has mainly been effective on lane L5; the effect on lanes L4 and L3 started around a kilometer upstream, and this congestion wave barely affected lane L1. 2) The evening peak period (16:00-19:00) when lanes L3 to L5 are highly congested throughout the study area. Moreover, lanes L1 and L2 exhibit congestion spillback from the Kennedy tunnel downstream, and overall, the speed drop is more drastic compared with the morning peak. 3) The off-peak period, when the free-flow regime dominates all lanes throughout the study area; speeds are higher on the fast leftmost lane L1 compared to lanes more to the right.

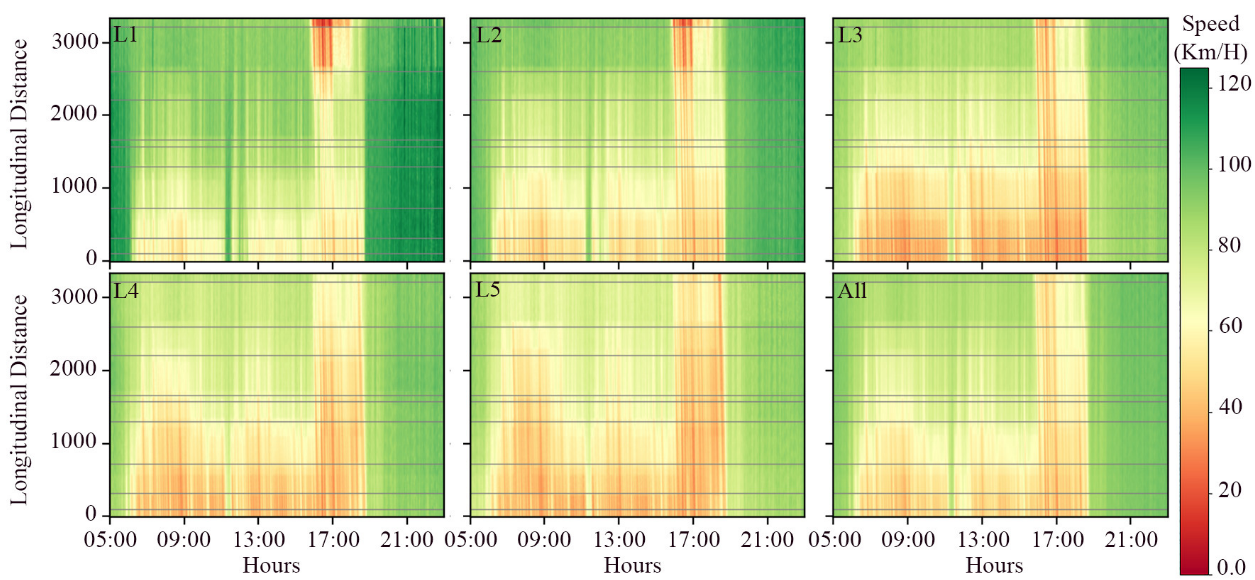

Figure 3 Lane-based traffic speed estimation for a representative day. Horizontal gray lines indicate the location of loop detectors, as identified in Figure 1. Lanes are numbered from left (L1) to the right (L5).

Figure 4, part (a) represents the hourly number of LCMs versus the total entry traffic flow toward the weaving area. Parts (b1) and (b2) show two-dimensional kernel density estimation (KDE) plots of mandatory and discretionary maneuvers in terms of delta speed and delta density between the target and source lane of LCMs. The same information is plotted in parts (c1) and (c2) of **Figure 4**, but this time categorized by maneuvers toward the left or right-hand side lanes concerning the source lane. Whereas, according to both criteria, maneuvers to the left have mainly resulted in driving in the lane with higher speed and less density, and in these respects, these maneuvers are entirely distinguished from maneuvers to the right; this distinction in the classification of maneuvers into mandatory and discretionary is not that much evident. Some other studies have reported a similar relationship between maneuver direction and speed gain (or loss) and change in lane density (14, 24). Among those studies, Ahmed et al. concluded that on average lane-changing vehicles drive faster and gain speed due to the LCM (25). Other studies indicated that speed and density gain or loss because of the LCM depends on the overall density condition of the segment, where in low and medium density conditions gaining better driving conditions (speed gain and lower density in target lane) is reported (26, 27), in high-density situation LCMs are not associated with gaining better driving conditions (28). It has also been shown that driving in faster lanes is an incentive to change lanes, and of course, this type of lane change has the potential for accidents (29).

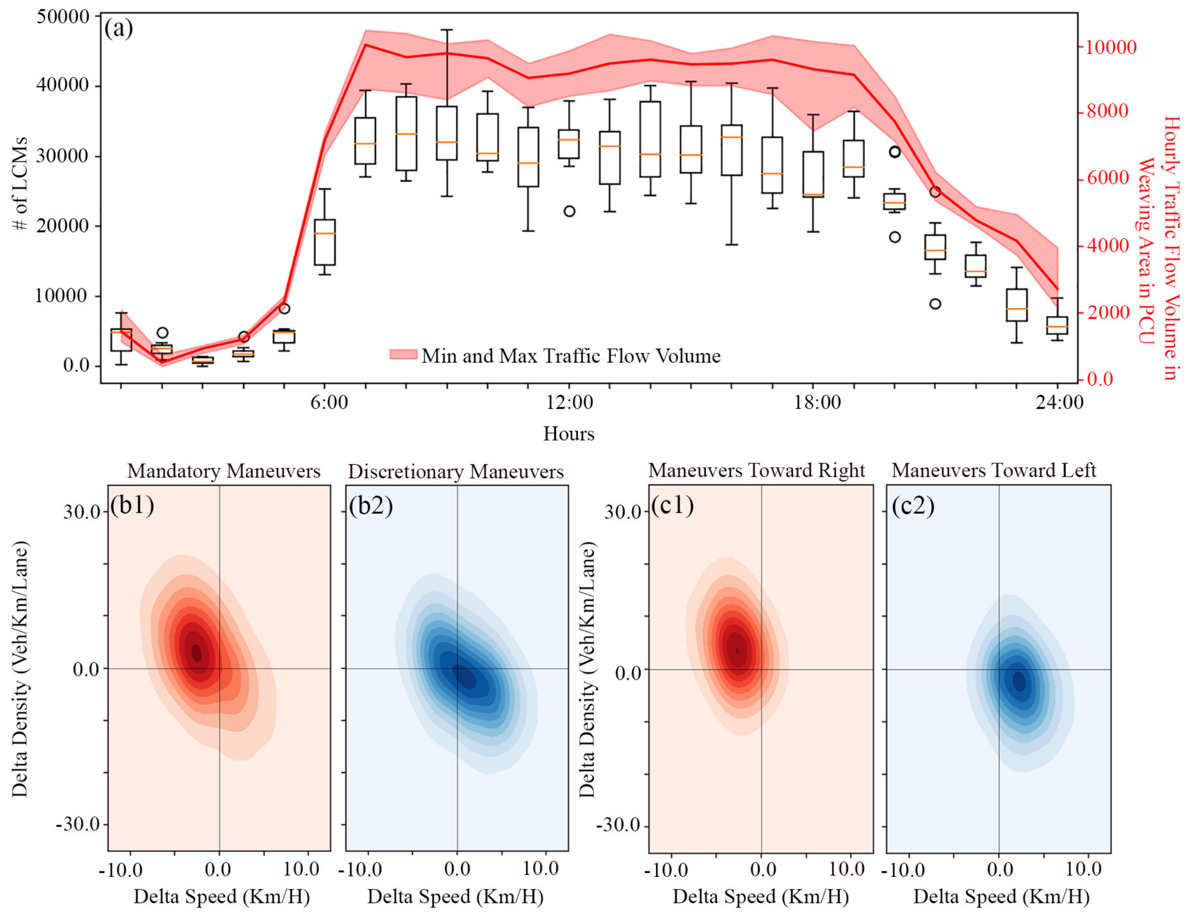

Figure 4 a) Hourly LCMs per hourly traffic flow entry to weaving area, b) Two-dimensional KDE plot of speed and density delta between target and source lanes categorized by mandatory and discretionary maneuvers. c) Two-dimensional KDE plot of speed and density delta between target and source lanes categorized by maneuvers performed toward the right or left with respect to the source lane.

From a behavioral point of view, categorizing maneuvers into mandatory and discretionary makes better sense. In **Figure 4**, the mean values of distributions are as expected. However, in panel (b2), we have some observations (15.7%) in the second quadrant (upper left) that indicate drivers performed a discretionary maneuver that caused a lower quality driving environment (in terms of speed and density). This seems counterintuitive and calls for more investigation: does our definition of discretionary maneuvers misclassify some mandatory changes for discretionary? or is it on certain occasions indeed preferable for a driver to be in another lane even if that target lane is denser and slower (but, for instance, a local gap is more attractive, there are fewer heavy vehicles, etcetera)? We can conclude from **Figure 4** that independent traffic variables might better describe the classification of maneuvers based on their direction. However, future research should decide whether this conclusion is valid only for the specific layout of our study weaving section or rather general and if it maybe depends on the way we have defined mandatory and discretionary maneuvers.

Behavioral Analysis of the Weaver Drivers

The main difference between weaver and non-weaver drivers is that weavers have to perform at least one mandatory LCM to reach their desired destination. The driving path of the weaver drivers who intend to reach D2 and originate from O1 based on their starting lane in R1 North might be associated with 1 to 3 mandatory LCMs. They also should cross lane L3, which is a conflict lane by the O2→D1 weaver drivers and shared with non-weavers of O1→D1. **Figure 5**, part (a) represents the scattering of LCMs of O1→D2 weavers. The cumulative distribution of their maneuvers location along the length of the study area is plotted in **Figure 5** part (b) for three different time periods. Moreover, parts (c1) to (c5) of this figure represent the two-dimensional KDE of delta speed and delta density between source and target lane of LCMs categorized by maneuver direction and target lane number.

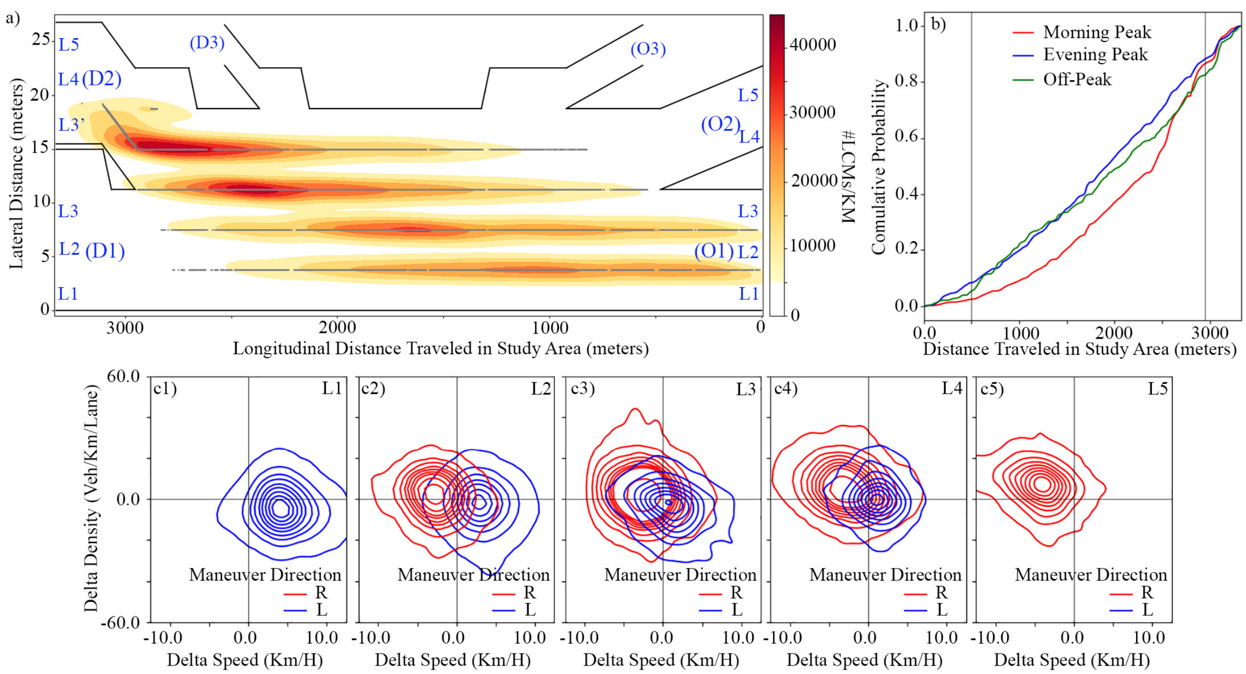

Figure 5 Behavior of weaver drivers from O1 to D2, a) The scattering of LCMs, b) The cumulative distribution of the location of LCMs along the length of the study area. Vertical lines represent the start and end points of the weaving segment., c1) to c5) Two-dimensional KDE of delta speed and delta density between source and target lane of LCMs categorized by maneuver direction and target lane number.

Part (a) of **Figure 5** indicates a vast number of LCMs happened in the very last 600 meters of the weaving area (between kilometers 2.3 and 2.9). Many behavioral reasons might lead to this pattern. Drivers' level of familiarity with traffic conditions and road geometry of the study area, as well as risk-taking versus risk-aversion personalities of drivers, are two suggestions. Simultaneous attention to **Figure 5** and **Figure 3** reveals the fact that between 6:00 and 16:00, a section of the study network where the highest concentration of LCM occurs, is associated with a significant increase in speed and mitigation of traffic congestion after several kilometers of speed drop and congestion in the network. As a possible hypothesis, drivers who are more familiar with this part of the road may have delayed their weaving behavior. They try to take maximum advantage of the higher speed in the left lanes. Another possible explanation for late weaving maneuvers could be related to the risk aversion of drivers who may have constantly delayed accepting the gap in the hope of finding a safer one downstream. Part (b) of **Figure 5** confirms this finding. Clearly, three distinctive weaving behaviors can be distinguished during the morning peak, evening peak, and non-peak periods. During the morning peak, less than 40% of the maneuvers are performed before kilometer 2.3, and more than 50% are performed just between kilometers 2.3 and 2.9. In the evening peak (consider the traffic state of this period in **Figure 3**), an approximately uniform distribution of LCMs is observable. This corresponds to the fact that during this period, the entire length of the network in almost all lanes is characterized by speed drops and high traffic congestion. Finally, although the distribution pattern of maneuvers in the non-peak period is not significantly different from the evening peak, two segments with a high slope are bold in the graph of this period. These two intervals are 200-300 meters immediately after the beginning of the weaving segment and 600 meters at its end. This means that a large proportion of drivers are early or late weavers during the off-peak period. Furthermore, it is worth mentioning that according to part (c) of **Figure 5**. Although maneuvering to the left is always associated with an increase in speed and a decrease in the density of the target lane, when moving from the left to the right of the panel (c), the change in the characteristics of the target lane with respect to the direction of the maneuver become less significant. The total length of this section is approximately 300 meters, and it is shown in figure 6 for clarity purposes.

In the investigation of the LCMs in the area after kilometer 2.6, which is the approximate location of the start of the D2 off-ramp, it should be considered that the increase of the lanes in this area is accomplished through a middle taper splitting lane L3 in L3 towards D1 and L3′ towards D2; lanes L4 and L5 continue uninterruptedly towards D2. Thus, for drivers being in L3 before the start of the middle taper, neither driving into L3 nor L3′ requires an LCM. This section's road marking is shown in **Figure 6**.

Figure 6 Lane extension section before Brussels off-ramp through a middle taper.

The same analysis is presented for weaver drivers who intend to reach D1 and originate from O2 through **Figure 7**. According to the starting lane of these weavers in E313, they might perform 1 or 2 mandatory LCMs. As stated previously, these weavers have conflicts on lane L3 with O1→D2 weavers and O1→D1 non-weavers.

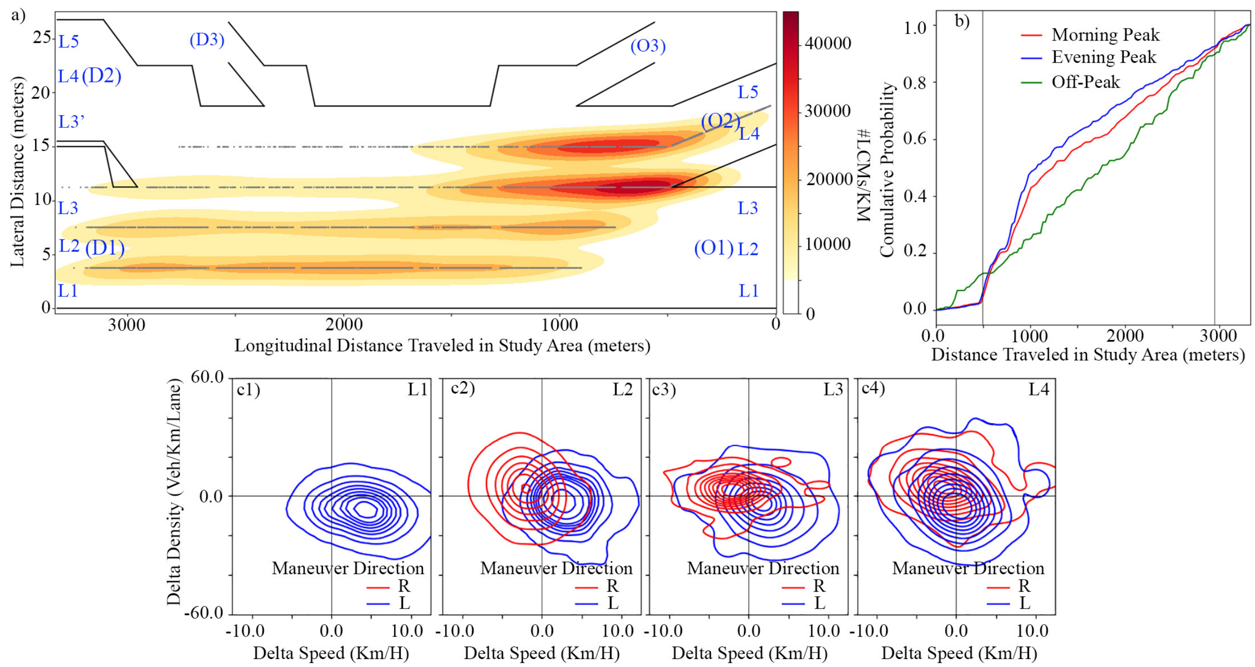

Figure 7 Behavior of weaver drivers from O2 to D1, a) The scattering of LCMs, b) The cumulative distribution of the location of LCMs along the length of the study area. Vertical lines represent the start and end points of the weaving segment; c1) to c4) Two-dimensional KDE of delta speed and delta density between source and target lane of LCMs categorized by maneuver direction and target lane number.

Based on part (a) of **Figure 7**, it seems that unlike weavers O1→D2, who were mostly late weavers, weavers O2→D1 are early weavers. A large fraction of the maneuvers of this group of drivers is performed only in the first 600 meters of the weaving section. This part of the network is almost consistently characterized by speed drop and traffic congestion from 6:00 to 19:00. So maybe one hypothesis for early weaving behavior would be that they are the winners of the conflict over lane L3. This means it is easier for them to leave lane L4 and join lane L3, which is associated with speed gain and hence acceleration compared to the weavers O1→D2, who lose speed in leaving lane L4 and joining lane L3 and should decelerate. The increased lane-change intensity in the weaving area and the associated space that drivers temporarily need simultaneously in two lanes causes capacity to be lower than in homogeneous motorway segments. An important question is whether the observed lane change patterns maybe make capacity even lower than this expected (and probably inevitable?) reduction, which would call for active traffic management strategies to achieve better cooperative behavior among drivers. Based on the Highway Capacity Manual (chapter 13) (30) applied to the parameters of this particular weaving section, we expect a theoretical capacity of around 10,625 PCU/h (on a 15-min basis). According to Figure 4, the total hourly discharge rate of the weaving area is bounded to a maximum of 10,050 PCU/h (on an hourly basis; 94.7% of theoretical capacity) with a rather high percentage of heavy vehicles: 20.2% (proximity of the port of Antwerp).

There are some interesting points to discuss in part (b) of **Figure 7** as well. During morning and evening peak periods, weavers wait to move to the left until they are inside the weaving segment. In contrast, in off-peak, about 14% of all maneuvers already take place in the last 500 meters of E313 before the weaving with R1 starts, after which the spatial distribution of LCMs is almost uniform throughout the rest of the weaving section. Part (b) of **Figure 7** confirms the findings of part (a) of this figure. During the morning and evening peaks, despite the later start of the LCMs toward the left, a large fraction of them completes already in the very first 600 meters of the weaving segment - about 40% and 46% of the whole morning and evening peak maneuvers, respectively. Furthermore, in both peak periods (especially during the morning peak), a substantial number of maneuvers that occurred between kilometers 1.7 and 2.7 aimed to increase speed and were directed toward lanes L1 and L2. The number of maneuvers towards lane L5 is scarce; hence it is statistically meaningless to draw the distribution of speed and density changes for them. In addition, the comparison of section (c3) in **Figure 5** and **Figure 7** can help to imagine better the deceleration and speed loss of weavers O1→D2 compared to acceleration and speed gain of weavers O2→D1 in their attempt to cross lane L3.

Another noteworthy aspect to discuss is the density in lanes L4 and L5, which is so high that entering those lanes is probably tricky. Therefore, it is probably highly desirable for O2→D1 weavers to leave these lanes and create gaps in L4 so that further in the weaving section, O1→D2 weavers can utilize those. This is a kind of beneficial self-organization driven by the density in the weaving lanes. The number of weavers is far less from O2 than from O1, but the density in O2 is indeed higher, as O1 has 50% more lanes than O2, but total demand from O1 is only 40% higher than from O2; hence, volume to capacity ratio on O2 is higher. The origin with the higher density has lower speeds, encouraging weavers from this lane to leave it as soon as possible while discouraging the ones in the faster lane from making an early maneuver. Contrary to what we observed a level of self-organization in drivers' LCM decisions, other studies found that LCM scheduling in current traffic flow is suboptimal, and intervention should (and will) optimize this within the weaving areas (31) or highway off-ramp (32).

In various studies, analyses similar to what we have done in part (b) of Figures 5, 7, 8, and 9 have been reported. Although compared to our exploration, those studies were limited in terms of network length and study period and did not provide detailed analysis categorized by different OD patterns and time of day, both early weaving (5-7) and late weaving (33, 34) behavior have been reported. Among them, even a very high rate of concentration of LCMs early in the weaving area is reported in Switzerland, where about 70% of the whole maneuvers occur within the first 19% of the section (35). Moreover, an approximately uniform distribution of LCM (36) and normal distribution of LCMs when the majority of maneuvers are fulfilled around the middle of the section (37) are also reported in the literature. Marczak et al. l concluded that speed is effective, and whereas slow vehicles change lanes early, the faster ones postpone it later in their pass through a waving area (38). Indeed, because almost all of the previous studies were done during the peak period, just one type of early or late weaving behavior was reported in each of the past explorations.

Figure 8 shows the travel time of the weaver's trajectory samples as a function of the location of their last crossing of the line separator between L3 and L4. The travel time is equal to the time each trajectory traveled inside the weaving area from entry to exit. In this diagram, we aggregated per 25 meters all trajectories that make their weaving maneuver within that interval. The Y-value shows the weighted average (with generalization factor as weight) of the travel time. Off-peak travel time for both weavings' flows are almost constant and independent of the weaving maneuver location, so it is only reported in **Table 2**. For the morning peak, **Figure 8** shows that the O1→D2 weavers have the benefit in postponing their weaving maneuver farther downstream: this group's travel time varies from 210 seconds for early weavers to 170 seconds for late weavers. In the evening peak, due to more uniform congestion, travel time is not affected by the location of the weaving maneuver and is almost constant at around 184 seconds. Alternatively, for weavers O2→D1 in both morning and evening peaks, both early and late weaving yields a lower travel time; maneuvers closer to the middle of the section experience longer travel times.

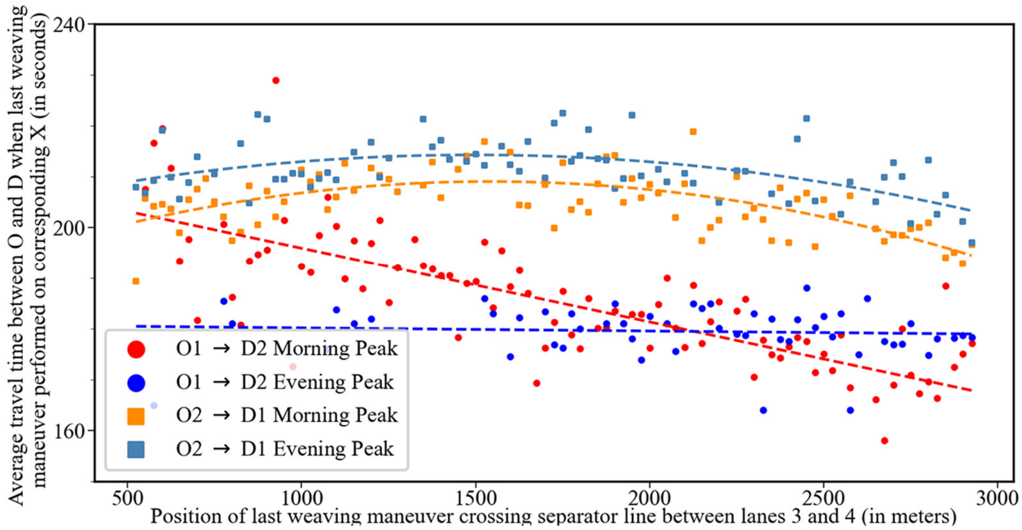

Figure 8 Travel time of the weavers as a function of the location of their last weaving maneuver and dashed lines represent the best-fitted curve/line (the number of trajectories represented by each point is varied).

Table 2 Average travel time by OD and time of day

Weaving pattern	Average travel time (seconds) Morning Peak	Average travel time (seconds) Evening Peak	Average travel time (seconds) Off-Peak
O1⟶D2	176.4	180.4	116.1
O2⟶D1	201.6	207.2	119.3

Our results so far imply that weaving in this section does not cause more capacity loss than one would theoretically expect. Improving discharge capacity by active (cooperative) traffic management may not be impossible. However, given the apparent efficiency of the self-organizing lane-change patterns (that seem to be driven by speed and density difference and, correspondingly: travel time gain), one needs to be careful not to let active intervention actually deteriorate the spontaneous processes rather than improve them!

Behavioral Analysis of the non-Weaver Drivers

Unlike weavers, non-weavers do not need to perform any LCMs to reach their destination. Therefore, it is expected that in the behavior of these drivers, the more straightforward act of lane keeping is dominant. Whereas they account for 22.96% of the total traffic flow between the four main OD pairs of the weaving section, they are responsible for 15.36% of all maneuvers. The analysis of the behavior of these drivers is presented in the graphs in **Figure 9**.

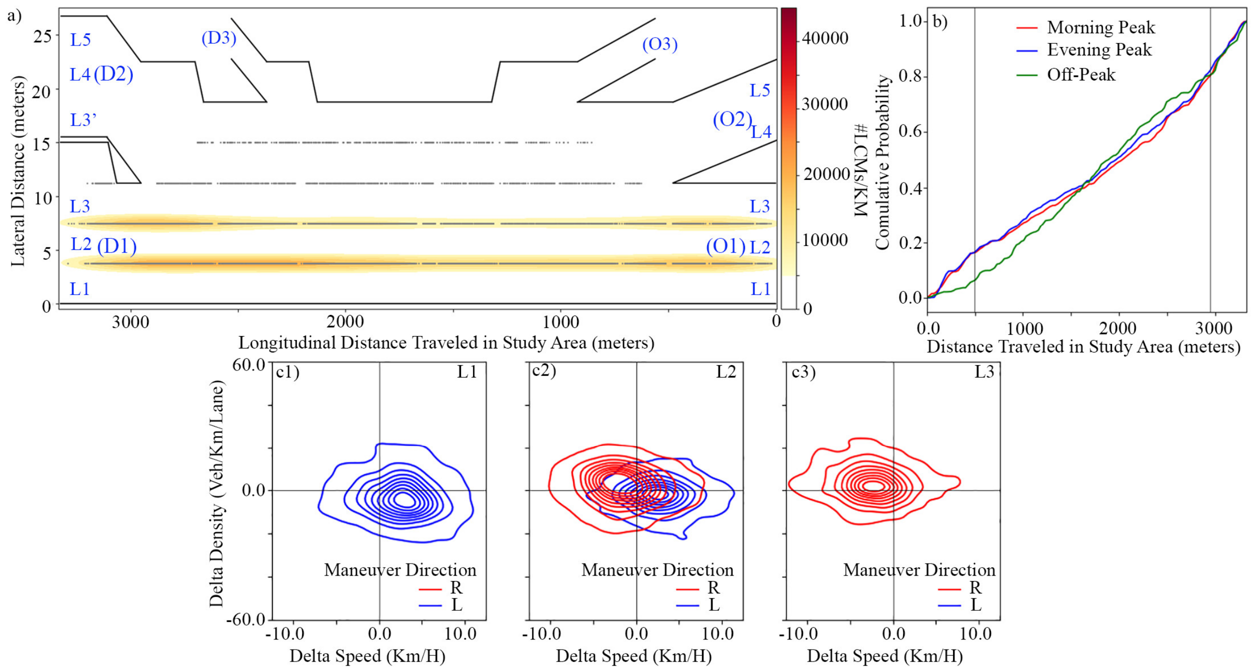

Figure 9 Behavior of non-weaver drivers from O1 to D1, a) The scattering of LCMs, b) The cumulative distribution of the location of LCMs along the length of the study area. Vertical lines represent the start and end points of the weaving segment., c1) to c5) Two-dimensional KDE of delta speed and delta density between source and target lane of LCMs categorized by maneuver direction and target lane number.

Figure 9 shows that, as expected, the majority of non-weaving drivers of O1→D1 have maintained their lane in most of their paths. Less than 2% of their LCMs were outside lanes L1 to L3 (towards lanes L4 and L5), which were related to heavy vehicles (trucks and buses). A noteworthy behavior of this group of drivers is the high share of the first 500 meters and the last kilometer of the study network from their total LCMs. In the first 500 meters of the study network, about 78% of the maneuvers were oriented toward the left. Then, in the last kilometer of the study network, most of the maneuvers were done toward the right. One possibility to explain this observation can be the attempt of drivers to avoid facing the spillback and speed drop that awaits them in lane L3 after the start of the weaving section. Although it may be selfish, this anticipating behavior of drivers might facilitate the merging of O2→D1 weavers. Part (b) of **Figure 9** shows that this anticipating behavior was strong in both morning and evening peaks, but much fewer drivers showed such behavior during the off-peak period. In part (c) of this figure, the diagrams for lanes L4 and L5 and the maneuvers to the left that targeted lane L3 are not provided because too few observations are available for all these maneuvers.

Non-weaver drivers of O2→D2 have performed even fewer maneuvers than non-weaver drivers of O1→D1. Their share of the total generalized maneuvers inside the study network is only 9.17%, while they comprise 17.1% of the total traffic flow. The same as what was presented for the other three groups of drivers, the behavior analysis of these drivers is illustrated in **Figure 10**.

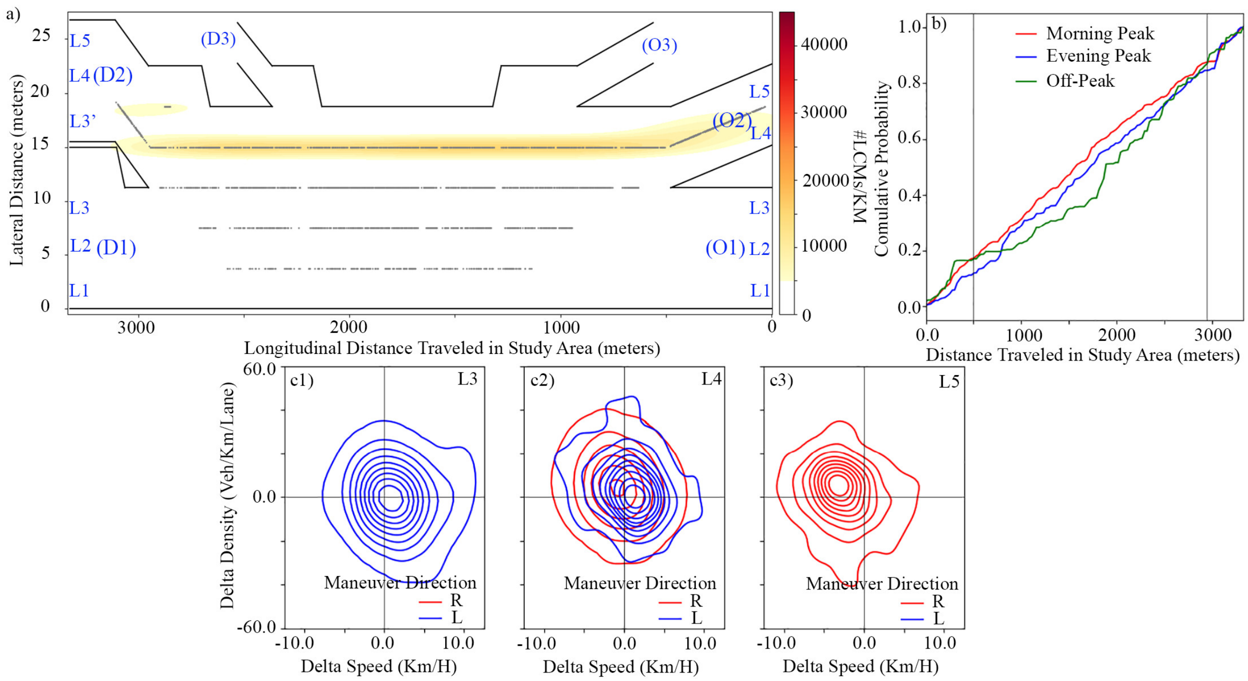

Figure 10 Behavior of non-weaver drivers from O2 to D2, a) The scattering of LCMs, b) The cumulative distribution of the location of LCMs along the length of the study area. Vertical lines represent the start and end points of the weaving segment., c1) to c5) Two-dimensional KDE of delta speed and delta density between source and target lane of LCMs categorized by maneuver direction and target lane number.

Figure 10, part (a) confirms that the maneuvers of this group of drivers are very low even compared to non-weavers O1→D1. In a limited number, some passenger cars can reach the left fast lane during the non-peak period. However, the share of maneuvers that crossed the lane separator between lanes L3 and L4 is only about 8% of the total maneuvers of this group of drivers. According to part (c) of this figure, LCMs do not cause a significant change in the speed and density of the target lane compared to the source lane. The reason is the heavy traffic congestion of lanes L3 to L5 during most of the day and over most of the length. In general, it can be concluded that the freedom for maneuvers of this group of drivers is very limited.

REMARKS AND CONCLUSION

This paper extends the state-of-the-art empirical analysis of lane-changing maneuvers. The analysis has been performed based on reconstructed trajectories collected through everyday conventional smartphones in a lengthy study motorway network, including a weaving area with an approximate length of 3.3 kilometers in the ring of Antwerp (R1), Belgium. The main feature of this paper is that we observed and interpreted some characteristics of LCMs that now, thanks to the reconstructed trajectories, are observable, while they could not be monitored before. For example, it is the first time that LCM behavior is reported in an extended weaving area with several on- and off-ramps during multiple days and for peak and off-peak periods. Our heatmaps that provide deep insight into LCM behavior depending on the driver route are unique. All previous studies covered at most a few hours of observation within a few hundred meters of the motorway, and sometimes the analysis is performed based on just less than a hundred observed LCMs, whereas in this paper, we report the results based on 14432 maneuvers (before generalization). The key contributions of the research are highlighted below:

- Although the classification of LCMs into mandatory and discretionary (i.e., by maneuver intention) provides a better definition of driving behavior, our analysis reveals that a classification of LCM behavior based on the direction has a better correlation with descriptive traffic variables such as changes in density and speed between the source and target lane. Therefore, it is highly recommendable that considering both classification criteria might be more effective in estimating LCM prediction models or calibrating traffic microsimulation software for lateral maneuvers.
- According to the best of the authors' knowledge in this paper, it is the first time that such a lengthy network has been used for the analysis of LCMs. We analyzed separately four origin-destination flows with sufficient sample size and showed that their LCM behavior differs substantially: not only do weaving and non-weaving drivers differ strongly (notably in their amount of lane changes), but also the two different groups of weavers represent very different behavior. Especially the place they choose for their weaving maneuvers is strongly related to their OD and the speed and density of traffic in the target lane.
- Another importance of this paper and its data is the continuity in the time of data collection so that we were able to provide separate analyzes for drivers' LCM behavior as a function of time of day (morning/evening peak and off-peak). In peak periods, the distribution of weaving maneuver locations along the length of the weaving section is heterogeneous and seems to be determined by opportunities offered (density) and speed gain that differs per OD; while in off-peak, maneuvers are in general more uniformly distributed with more room for personal preferences (mild concentrations of both late and early weavers).
- In this paper, we have shown that the travel time of different weavers does not only correlate with their origin and destination but even more so with the place where they perform their weaving maneuvers.

The results in this paper are the first analyses of newly obtained data (18), which calls for further and deeper analysis. For instance, **Figure 4b** suggests that many discretionary LCMs would target slower and denser lanes. This could either mean that other benefits may be stimulating discretionary lane changes or that better criteria to distinguish them empirically from mandatory maneuvers are needed. Another unexplored aspect of the dataset is the more sparsely sampled flows originating from O3 or destinated toward D3 (which may, despite its low volume, have a substantial impact on congestion, given its interaction with the more significant weaving flows and need to cross the dense lanes L4 and L5) or focusing on special vehicle classes such as trucks. Moreover, in this paper, we studied recurrent traffic congestion; patterns formed because of traffic accidents or unusual weather conditions might be another interesting topic for research. In addition, the complete border of our data collection started kilometers long before the weaving area. This gives us the ability to explore driving styles (such as aggressive, selfish, cautious, and collaborative) and their effect on LCM behavior. Finally, one may consider to what extent the results of this paper are valid for other weather, traffic, and road geometry conditions. For example, consider the patterns of weekends instead of weekdays. Alternatively, differentiating between the behavior of different vehicle types (e.g., passenger cars versus trucks) and considering different traffic compositions in terms of the rate of heavy vehicles.

Furthermore, one may use the results of this paper for calibrating microsimulation software for lateral movements and evaluating different management strategies to orchestrate drivers' LCMs aimed at a higher-quality traffic flow in weaving areas. Literature is full of attempts to calibrate traffic microsimulation software. The majority typically use macroscopic data, such as volume and average speed on cross-sections where loop detectors are located. Very limited efforts have been reported in the literature aimed at microsimulation calibration based on lateral maneuvering data (39). Due to the complexity of LCMs around ramps and especially in weaving areas, even the most meticulous calibrations still fail to reproduce traffic flow characteristics in such segments. A plausible reason is the lack of availability of LCM observations in different segments, times, and congestion levels. Given our new data, it now becomes possible to develop calibration objective functions based on LCM criteria. For instance, the heat map of LCMs that we provided in this paper might be a target to be compared with corresponding spatio-temporal distribution of LCMs extracted from the microscopic traffic simulators. It remains an open challenge for the analyst to define a suitable similarity measure between observed and simulated distributions to guide the calibration. If despite such efforts, parameter calibration may fail to reach sufficiently similar LCM distributions, then the type of results provided in this paper might help microsimulation software developers to come up with more effective lane-change mechanism logic. For example, the results of this paper suggest that drivers do not just develop a lane change desire based on the distance to the exit gore, but that in addition to this factor, also speed and density difference between source and target lane play an important role.

We believe that a level of self-organization is observable in the behavior of weaving flows in the study network. It is not easy to judge whether still more efficient behavior can be achieved. Future studies might investigate the optimization of the geometric design of weaving areas and active management of these areas based on giving priorities to different weavers in different segments of a weaving area. Apart from geometric design parameters like the number of lanes and weaving length, one might assign different segments of the weaving area to different groups of weavers through horizontal road marks (solid and dashed lines). Moreover, active management via public intelligent transportation systems or sending tailor-made recommendations through navigation applications for drivers might help to migrate from a set of selfish user optimum decisions taken by every individual driver toward a system optimum condition orchestrated by a central management unit. It is the task of future studies to determine whether such an optimal system state exists and how different it is from current self-organizing conditions.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Arman, Tampère; data collection: Tampère; analysis and interpretation of results: Arman, Tampère; draft manuscript preparation: Arman; final manuscript preparation: Arman, Tampère. All authors reviewed the results and approved the final version of the manuscript.

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