Empirical Analysis of Lane Changing Maneuvers in Motorway Weaving Area

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SHORT SUMMARY

A lane-changing vehicle effectively occupies two neighboring lanes for a few seconds. In complex sections of motorways networks, especially in weaving areas, the rate of these maneuvers is significantly higher. This is the primary source of turbulence in flow, which results in a decrease in speed, density, and flow quality. There is a significant research gap in the empirical analysis of lane-change maneuvers. This paper presents an empirical analysis of lane change maneuvers in a weaving area in a motorway network with a length of about 3.1 km. Differences in traffic characteristics between the source and target lanes, such as flow volume, density, and speed, were shown to incentivize drivers to undertake lane change movements. However, while discretionary maneuvers are usually associated with easier driving conditions, in most cases, the mandatory maneuvers have been towards slower lanes or with higher flow volume and/or density.

Keywords: Traffic empirical analysis, Lane changing maneuvers, Driving behavior, Motorway weaving areas

1. INTRODUCTION AND LITERATURE REVIEW

When a vehicle is maneuvering to change its lane, it effectively occupies two adjacent lanes for a few seconds. In complex sections of motorways networks, especially in weaving areas, the number of lane change (LC) maneuvers is significantly higher. This causes the distribution of speed, headway, and density in different lanes to be unbalanced. This situation causes traffic disturbances, which is well known as turbulence in the literature. Turbulence (and consequently LC maneuvers) is the most important factor in speed drop, density drop, and reduction in quality of traffic flow and also leads to a decrease in traffic safety.

Although many studies have been conducted in the field of longitudinal driving behavior, the literature on lateral driving behavior studies is relatively poor. The most effective factor in this research gap is the lack of (or at least the shortage of) appropriate data for these studies. The appropriate data for LC studies is trajectory data. The length and number of trajectory samples are very important in the quality of the study. A common way to collect this data is video recording and then image processing. However, this method suffers from two important drawbacks. The first is that it is fairly expensive, and the second is that it is not possible to cover a long section of the road network. High-precision reconstruction of trajectories recorded by smartphones is another source. However, such data is not publicly available. The present study deals with the empirical analysis of LC maneuvers in a weaving area on a motorway network around Antwerp, Belgium.

Olsen et al. had studied the LC behavior of 16 drivers in their commuters' daily trips when the drivers were aware of the study in long commuting paths of the average length of 60.2 km and they have concluded that higher traffic densities lead to significantly more lane changes (Olsen et al. 2002). In another study, 4 CCTVs were used to investigate the relationship between LC maneuvers and the speed and density of traffic flow in different lanes of the weaving areas of urban highway segments with a length of 200 to 300 meters (Xie, Jiang, and Zhang 2011). The study of drivers' LC maneuvers in urban street networks has shown that increasing density increases drivers' desire to accept shorter headways to perform maneuvers (Gurupackiam and Jones Jr 2012). Knoop et al. have described density as the most important factor in the rate of LC maneuver and have stated that an increase in density at both the source and target lanes is associated with an increase in the rate of LC maneuvers (Knoop et al. 2012).. Using a stochastic approach in analyzing NGSIM data revealed that speed and spacing are effective factors in drivers' LC maneuvers (Lee, Park, and Yeo 2013). An empirical study of LC maneuvers in a weaving section with a length of 535 meters in Switzerland has shown that 80% of the weaving lane changes and 30% of the non-weaving lane changes are performed in the first 100 meters of the weaving section. The analysis has led the authors to conclude that if the drivers can be persuaded to use the entire length of the section for weaving LC maneuvers, the performance and practical capacity of the section will be improved (He and Menendez 2016). Yang et al. separated the LC and overtaking maneuvers and concluded that as the density increases, the rates of both maneuvers increase. In addition, they have found that in denser traffic flows, drivers more sharply accelerate to perform both types of maneuvers (Yang et al. 2018).. A study comparing the practical capacity of the weaving sections based on the empirical data of lane-change maneuvers and comparing it with the formula of the Highway Capacity Manual has confirmed that the rate of LC maneuvers is directly increased with the increases of the density in the weaving section. This study has concluded that increasing 150 to 600 meters in the length of weaving sections can only reduce the density of the section by about 6% (Ahmed et al. 2019). In a study that examined the duration of LC maneuvers, it was claimed that this time had a significant inverse relationship with vehicle speed and acceleration, whereas the relative speed and relative acceleration of the vehicle with its leader had no significant relationship with the LC maneuver time (Yuan, Li, and Bao 2020). In addition, analyzes based on the behavior of LC maneuvers in driving simulators have been performed, which are beyond the scope of this study (Ali, Zheng, and Haque 2018; Yuan et al. 2019).

While all the existing empirical studies have explored the LC maneuvers in small road segments, this paper presents the empirical analysis of the LC behavior affected by the traffic conditions of the source and target lanes in a long road segment of approximately 3.1 km. The most important contribution of this paper can be summarized in two points. First, we provide the correlation between the traffic variables and the decision to perform mandatory and discretionary LC maneuvers that can be used to estimate LC decision models. And the second could be the calibration of LC behavior in traffic microsimulations. This paper shows that, contrary to popular belief, all discretionary LC maneuvers are not oriented to easier driving. Rather, some of them are anticipating behavior, and although they immediately lead the driver in a lane of lower speed (higher density and/or volume), they prevent the driver from getting tacked in a queue downstream.

2. DATA COLLECTION

The test site of this paper consists of a weaving area in the inner motorway ring R1 near Antwerp, Belgium. The data was collected through passive observation of existing users of the Touring Mobilis and Flitsmeister smartphone apps of commercial traffic service provider Be-Mobile available for iOS and Android operating systems. This weaving area is a part of a bigger highway network. A geofence was defined around the weaving section. Upon entry of the geofence, trajectory data is recorded at 1 Hz frequency of each vehicle in which a user has this smartphone app installed. Because the drivers are completely anonymous and uninformed (other than their general consent, upon installation of the app, to collect and exchange anonymized data), there are no driving instructions. As a result, drivers are unaffected by passive surveillance and decide independently on their driving lanes and maneuvers such as lane change and overtaking. The collected trajectories are then reconstructed based on a high-precision data-fusion-based method that reduces the lateral error to less than the width of a standard lane in highway networks (Arman and Tampère 2021). The weaving area in highway network around Antwerp as well as an abstract sketch of it, is shown in Fig. 1.

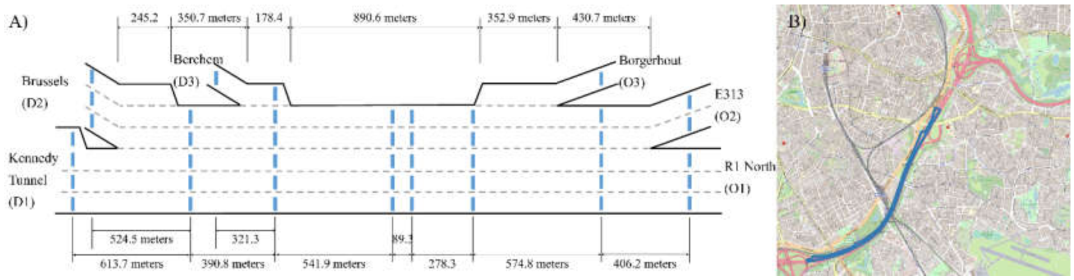

Fig. 1. A) abstract sketch of the weaving area (total length of 3.1 Km), the blue rectangles representing the loop detectors, flow direction is from right to left. B) Location of the weaving area in the highway network around Antwerp

3. DATA ANALYSIS AND RESULTS

For the analyzes presented in this paper, a total of 7033 trajectories (almost 1% of total daily flow) collected during 6 working days in September and December 2019 have been used. In order to provide a comparison of the lane change behavior in different traffic conditions (speed, flow, density and etc.), all-day data is utilized. Considering the volume of incoming and outgoing traffic from each of the origins and destinations in Fig. 1 to/from the weaving area and the number of trajectories that have traveled between each OD pair, the generalized OD matrix has been computed by the Furness method. The generalized OD matrix, and the generalization factors, are presented in in Table 1. The table represents the average and in parentheses standard deviation of the six days. Due to the very large generalization factor obtained for the trajectories of the origin and destination 3 (which means their sample size is very small), these trajectories have been excluded from the continuation of this study.

Table 1. Daily traffic flow and percentage of trajectories based on the origin and destination in weaving area

	Generalized Daily OD Matrix			Generalization Factors		
	Kennedy Tunnel (D1)	Brussels (D2)	Berchem (D3)	Kennedy Tunnel (D1)	Brussels (D2)	Berchem (D3)
R1 North (O1)	22118 (3774.5)	39118 (9709.4)	7655 (1290.0)	61.1 (10.4)	79.7 (19.8)	332.2 (43.0)
E313 (O2)	24330 (1038.6)	16483 (3462.3)	5654 (1502.8)	151.2 (9.2)	138.5 (39.3)	942.4 (250.5)
Borgerhout (O3)	5495 (2495.6)	8564 (2540.4)	1700 (2561.6)	1831.6 (831.9)	1229.8 (508.1)	1273.9 (640.4)

A total of 34,368 lane changes were identified in the road segment shown in Figure 1, which is equivalent to 1.58 (StDev = 0.57) LCM/vehicle/km. In a similar study in China, this number was calculated to be 1.04 on a straight section of road without any on/off-ramps (Guo, Wu, and Zhu 2018). Also, according to the data presented in two separate studies in two weaving areas in California and Baltimore, this number is 0.89 and 1.97, respectively (Bham 2006; Goswami and Bham 2006).

The identified lane change maneuvers are categorized into mandatory and discretionary maneuvers. In this paper, all the maneuvers which have been done by a vehicle after leaving an on-ramp that merges the vehicle in the mainstream traffic flow and all the maneuvers which have been done by a vehicle before diverging toward an off-ramp from the mainstream traffic flow are considered as mandatory lane changes. Overall, 21.36% of all observed lane changes were mandatory. Considering Fig. 1 and Table 1, it can be realized that most of the mandatory maneuvers are due to joining from the E313 on-ramp to the mainstream or diverging from the mainstream toward Brussels. Let's call the drivers who do these maneuvers a weaver driver (WD). In total, 57.43% of the total trajectory samples are WDs. However, they are responsible for

72.15% of all lane changes in the study area. Consequently, the average lane changes in the study are 2.05 LCM/vehicle/km and 1.07 LCM/vehicle/km for WDs and non-WDs, respectively. These numbers indicate how much it would be possible to improve the practical capacity of the weaving area if it becomes possible to manage weaver drivers' LC maneuvers using intelligent transportation systems (ITS). Fig. 2 shows the scattering of these two types of lane changes as well as all the LCMs of WDs. The figure represents the generalized maneuvers.

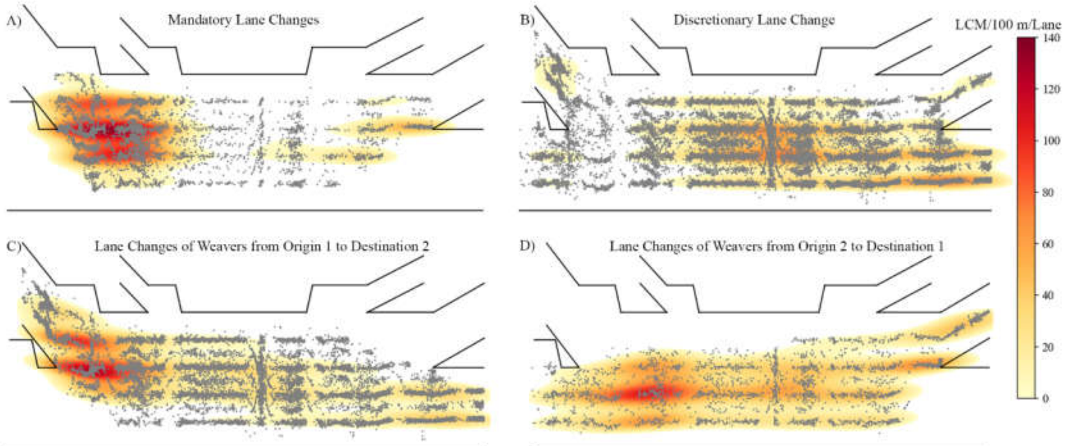

Fig. 2. Scattering of discretionary and mandatory lane changes maneuvers as well as all lane changes of the weaver drivers

While discretionary maneuvers are scattered throughout the study area (part B), the mandatory maneuvers are concentrated after on-ramps and before off-ramps (part A). Comparing panels, A and D reveals that the drivers who had weaving behavior from origin 2 to destination 1 mainly performed their merging maneuvers a few hundred meters after the point of connection of the on-ramp to the mainstream. The average distance between the mandatory merging to the mainstream is 359 meters, and the farthest and closest observed distances for this maneuver are 1615 and 27 meters, respectively. On the other hand, comparing panels, A and C shows that the drivers who had weaving behavior from origin 1 to destination 2 mainly had a non-mandatory maneuver before the connection ramp of origin 2. It seems this maneuver is toward the left, and the reason can be considered to prevent encountering weaving vehicles that come from the origin 2 to the mainstream. The mean, the maximum, and minimum distances for diverging from the mainstream are 482, 1541, and 35 meters, respectively. Regarding the mandatory maneuvers, it is noteworthy that there are two groups of late weavers and early weavers of drivers. This can be related to some drivers' characteristics such as risk-taking or risk-aversing or their familiarity with the road network.

If the lane-changing maneuver is not performed for a mandatory reason, the most common reason is to overtake. In this case, the driver's target lane is expected to be faster, with less traffic flow volume and density than the source lane. In addition to overtaking, a driver (usually of passenger cars) may feel uncomfortable (or unsafe) moving between trucks and prefer to drive on lanes with a more homogeneous flow concerning the length of his/her car. The driver may also change lanes because s/he expects to get stuck in a queue that built up downstream of this lane. In this case, the driver may perform an anticipating lane changing intended to future easier driving. At the same time, it may put the driver in a lane with lower speed and higher flow and density in the short term after the maneuver.

To analyze whether such expectations on driving behavior are justified, the changes of four traffic variables in the target lane compared to the source lane along with the change in vehicles' acceleration are examined in the following. These four variables are the volume of traffic flow, density, speed, and standard deviation of vehicles' length (homogeneity), respectively.

Fig. 3 and Table 2 show the changes in the volume of traffic flow in the target lane compared to the source lane for mandatory and discretionary maneuvers. As expected, most vehicles that underwent mandatory maneuvers (62.4%) entered the lane with higher traffic flow volume. In comparison, this percentage is only 25.3 for vehicles that have undergone discretionary maneuvering.

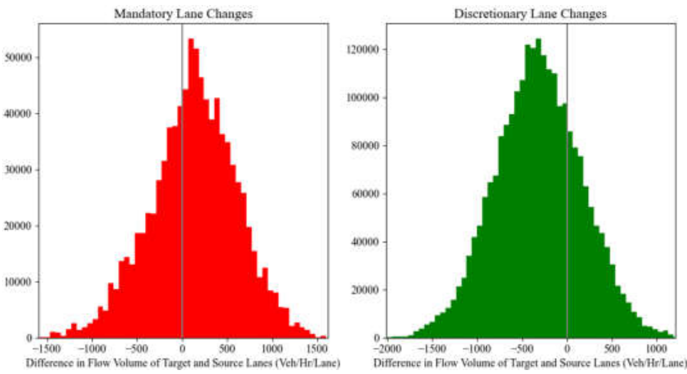

Fig. 3. Histogram of difference in traffic flow volume between source and target lanes

Table 2. Difference in traffic flow volume between source and target lanes

	Mean	Standard deviation	Minimum	Maximum
Discretionary LCMs	-315.72	495.68	-2360	1720.0
Mandatory LCMs	131.14	490.14	-1585	1775

Another important point about the relationship between traffic flow volume and LC maneuvers is the direct relationship between these two (Pearson correlation = 0.77). Fig. 4 shows the number of LC maneuvers per hour in 6 days of study along with the hourly volume of traffic flow. The blue graph on the right-hand side shows the number of maneuvers in each hour divided by the volume traffic flow of that hour. It can be seen that the increase in traffic volume has always been accompanied by an increase in the number of LC maneuvers (according to the blue graph, each vehicle has performed more LC maneuvers). And the pattern of changes in the number of LC maneuvers per hour during the morning and evening peaks is significantly similar to the pattern of changes in the volume of traffic flow during these hours. A second-order polynomial relationship holds between hourly flow and hourly number of LCMs.

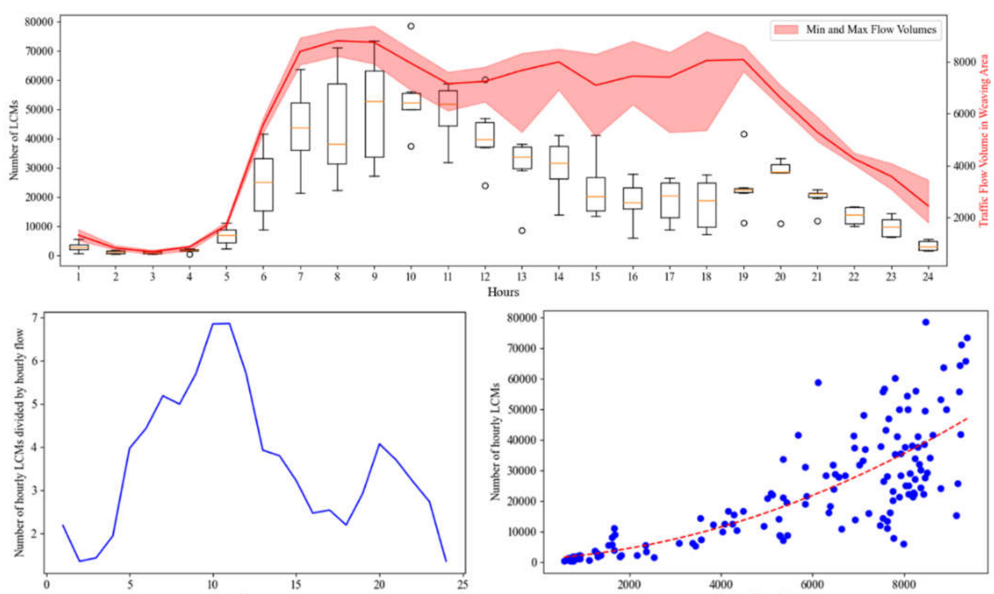

Fig. 4. Hourly pattern of number of LCMs, traffic flow volume and LCM/Veh/Hour

Fig. 5 and Table 3 show the density changes in the target lane relative to the source lane separated for mandatory and discretionary maneuvers. The same pattern can be seen here, and on average, vehicles that have performed a mandatory maneuver have gone to lanes with higher density compared the source lane. In total, 57.4% of the total of these LC maneuvers has targeted the lane with a higher density than the source lane. In contrast, for those vehicles that have performed a discretionary maneuver only 23.3% have switched to a denser lane.

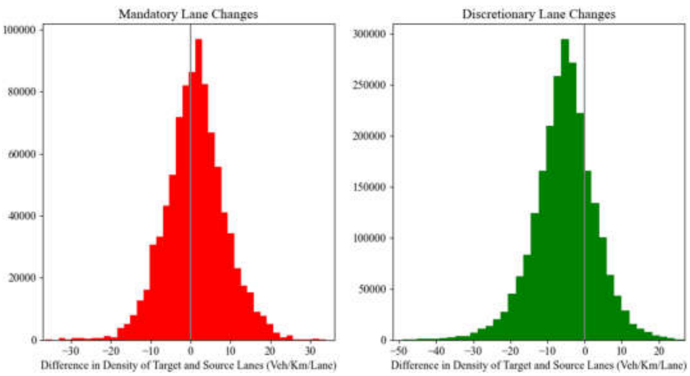

Fig. 5. Histogram of difference in density between source and target lanes

Table 3. Difference in density between source and target lanes

	Mean	Standard deviation	Minimum	Maximum
Discretionary LCMs	-5.38	8.67	-49.2	26.9
Mandatory LCMs	1.23	7.76	-37.1	36.1

The histogram and statistics of the speed changes in the target lane relative to the source lane, separated for mandatory and discretionary movements, is shown in Fig. 6 and Table 4. The analysis of the change in speed from the source lane toward the target lane also confirms the analysis of the previous two variables. Almost 70.8% of discretionary maneuvers were accompanied by speed gain. On the other hand, in the case of mandatory maneuvers, only 32.1% of these maneuvers involved joining a faster lane than the source lane.

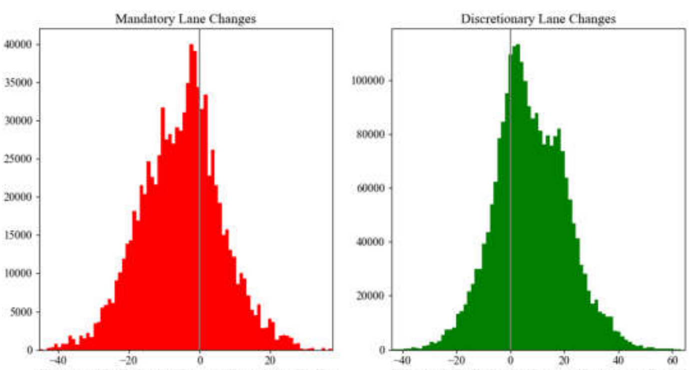

Fig. 6. Histogram of difference in speed between source and target lanes

Table 4. Difference in speed between source and target lanes

	Mean	Standard deviation	Minimum	Maximum
Discretionary LCMs	7.48	13.47	-44.1	64.8
Mandatory LCMs	-5.21	11.53	-45.5	37.7

The histogram of changes of homogeneity in the length of vehicles in LC maneuvers from the source lane to the target lane and the statistics of these maneuvers are presented in Fig. 7 and Table 5. In the case of mandatory maneuvers, vehicles must first enter the shoulder lane after leaving the auxiliary lane. In the study network of this paper, this lane is mainly occupied by trucks. Therefore, due to the weaving maneuvers of other vehicles, this lane is usually the most heterogenous lane. Accordingly, for mandatory maneuvers, lane changes are mostly targeted to heterogeneous lanes. This phenomenon has been observed for approximately 63.2% of these maneuvers. In contrast, Figure 6 for discretionary maneuvers (green graph) is more centered around zero, and only 40.0% of vehicles that have performed this maneuver have gone to a more heterogeneous lane.

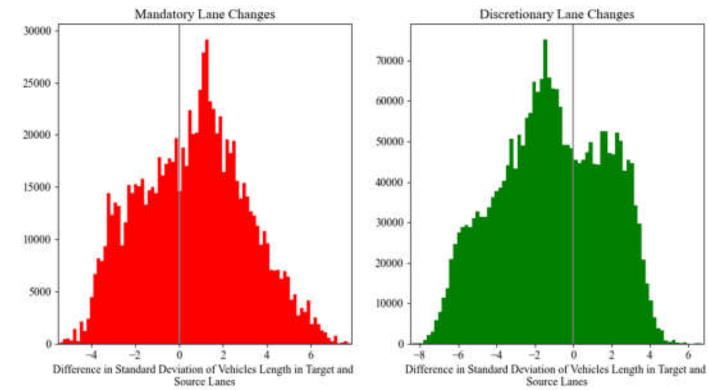

Fig. 7. Histogram of difference in standard deviation of vehicles' length between source and target lanes

Table 5. Difference in standard deviation of vehicles' length between source and target lanes

	Mean	Standard deviation	Minimum	Maximum
Discretionary LCMs	-1.10	2.79	-8.51	6.82
Mandatory LCMs	0.63	2.45	-5.53	7.86

The histogram of the acceleration that the vehicles have adopted to perform their LC maneuvers, along with the statistics of this variable, is shown in Fig. 8 and Table 6. Although it may be expected that lane changing toward a slower lane or diverging from the traffic mainstream toward on-ramps will always be associated with deceleration, we find that even in cases where the vehicle has shifted to a slower lane, it still may accelerate in some cases (17% of mandatory maneuvers to slower lanes and 35.5% of discretionary maneuvers to slower lanes). In total, approximately 94% of discretionary maneuvers and almost 44.4% of mandatory maneuvers were accompanied by acceleration.

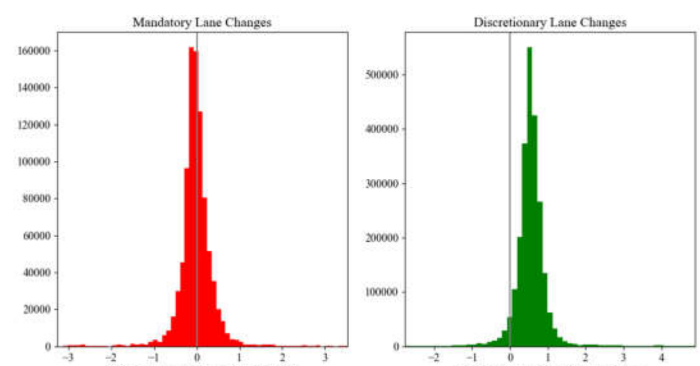

Fig. 8. Histogram of acceleration and deceleration during lane changing maneuvers

Table 6. Acceleration and deceleration during lane changing maneuvers

	Mean	Standard deviation	Minimum	Maximum
Discretionary LCMs	0.55	1.90	-2.77	4.89
Mandatory LCMs	-0.04	1.97	-3.27	3.52

4. CONCLUSION AND REMARKS

This paper deals with the empirical study of lane change maneuvers in a weaving area with an approximate length of 3.1 km in a motorway network. In the study of 7033 trajectories, a total of 34,368 LC maneuvers were detected, which is equivalent to 1.58 LCM/veh/km. Due to the high volume and density of traffic flow in most segments of the study weaving area and the presence of two on-ramps and two off-ramps, we can expect what effect this number of LC maneuvers will have on reducing the capacity and traffic quality. We also showed that differences in the traffic characteristics of the source and target lanes could motivate drivers to perform LC maneuvers. However, while discretionary maneuvers are usually associated with easier driving conditions (increase in speed, decrease in flow volume and/or density, etc.), in most cases, the mandatory maneuvers have been towards slower lanes or with higher flow volume and/or density. Finally, we have shown that majority of the discretionary maneuvers and about 44% of the mandatory ones that performed intending to merge and diverge and usually towards slower lanes are associated with acceleration.

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