Empirical comparison between longer and shorter weaving sections in Switzerland

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Abstract

Freeway weaving section is characterized by an on-ramp closely followed by an off-ramp. The merging and diverging maneuvers of vehicles from the on-ramp and off-ramp interact with each other. This could cause bottlenecks on the freeway and might reduce its capacity. Since the interaction of the conflicting traffic streams is the source of the problem, concentration of lane changes is conjectured to have negative impacts on the operation of freeway weaving sections. To this end, this research identified and analyzed two weaving sections in Switzerland with different section lengths. The goal is to see if there are difference in their operation due to difference in section length. The lane change behaviour in these two weaving sections are analysed in detail.

Keywords

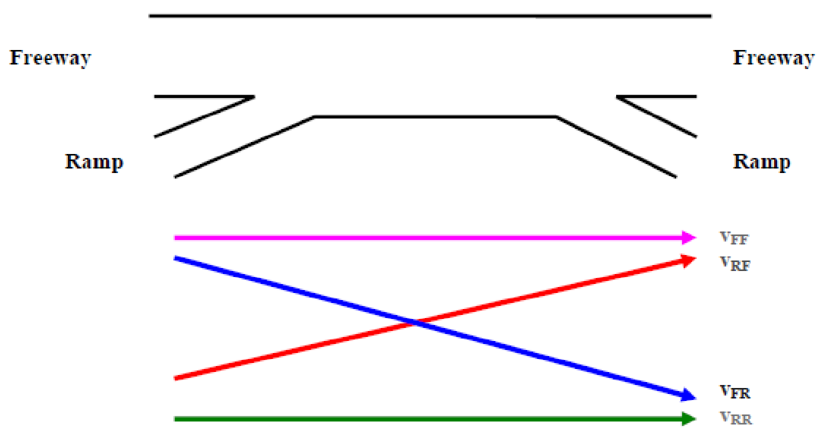
weaving section – lane change – bottleneck

1. Introduction

A weaving section, defined as a road section where an on-ramp is followed by a nearby off-ramp, causes different driving maneuvers, as illustrated in Figure 1. The merging and diverging maneuvers of vehicles from the on-ramp and off-ramp interact with each other. This could cause bottlenecks on the freeway and might reduce its capacity.

There are four types of flows involved in a weaving section as illustrated in Figure 1. Since it was not possible to track individual vehicle O-D in our empirical study, the four flows are estimated as follows. Freeway-to-freeway (F-F) flow is approximated by the total flow of lane 1 and lane 2 at the merge minus the lane changing rate from lane 2 to lane 3. Freeway-to-ramp (F-R) flow is approximated by the lane changing rate from lane 2 to lane 3. Ramp-to-freeway (R-F) flow is approximated by the lane changing rate from lane 3 to lane 2. Ramp-to-ramp (R-R) flow is approximated by the flow of lane 3 at the merge minus the lane changing rate from lane 3 to lane 2. Notice that this assumes that vehicles do not change to lane 3 for overtaking. This is reasonable in Switzerland as such usage at lane 3 is illegal.

Figure 1 Illustration of a weaving section and the associated four types of flows.



2. Weaving area Winterthur Nord/Wülflingen (570m)

2.1 Site description

This weaving section represents weaving type B0. This type of weaving section has three lanes (two through lanes and one ramp lane), and is relatively long. In our case, the weaving section is 570m long. An on-ramp comes from another highway section from the direction of Schaffhausen. Therefore, most of the vehicles merge to the highway and only a few continue on the auxiliary lane to the off-ramp. The off-ramp separates traffic streams between local destinations, such as Wülflingen, Pfungen and continuing traffic streams on the Highway A1 towards Zurich. Therefore, the R-F flow is significantly higher than the F-R flow. The total traffic volume per day is about 50’000 vehicles and the speed limit is set to 100km/h. The entire section is located in a slight bend. The morning peak hour has more traffic because many drivers commute from Schaffhausen or St.Gallen towards Zurich.

2.2 Measurement and data description

The morning peak period was chosen for measurement for this site on 5 days (June 26th, June 29th, June 30th, July 1st, and July 2nd). On each day, measurement was carried out for about 5 hours, but only 3 days were chosen for analysis. The days with the most normal circumstances (i.e. without accidents or excessive downstream congestion) are chosen. For each of the 3 days, 3 hours of data were extracted. The periods of extraction were chosen to cover the entire congestion period (i.e. it starts when the traffic is uncongested and ends after the traffic has returned to uncongested state.). Since the traffic is congested over slightly different periods, the periods of data extraction for these three days are a little different.

Five video cameras were installed. Three on an over-crossing bridge, one under the bridge and one on a wall at the merge location. Recordings and installation positions of them are illustrated in Figure 2. Two radars were installed to cover the merge area and a middle area as illustrated in Figure 3. The diverge area was not covered because from the results of the pilot site, the road segment at the diverge seems to operate similar to a normal highway segment. Therefore, it does not provide much additional information to measure traffic at the diverge. Traffic at a middle location was measured to provide insight into how traffic states changes from the merge, where intensive lane changing activities could activate a weaving bottleneck, to the diverge, where there is not much lane change activities and the road segment operates as a normal highway segment. The radar at the merge was installed on a military mast. The radar at the diverge was installed on a highway the over-crossing bridge. Each of the radars could cover about 100 meters as illustrated with the brackets. Note also that there is a loop detector near the off-ramp location.

Three kinds of data were extracted from the measurement. Firstly, manual vehicle counting was made from the video recording at two locations along the weaving section: at the merge and in the middle of the weaving section. Counting at the diverge was also extracted from loop detector data. All counting data are available for each lane, and vehicles were classified into cars and trucks. The flow at the merge and diverge could then be calculated from the counting. Secondly, the speed of the vehicles was directly extracted from the radars. The speed of the detected vehicles at each location is assumed to be a sample estimate for the speed of all vehicles passing that location. An estimate for the space mean speed is calculated by taking the harmonic mean of the speeds of the detected vehicles. With both the flow and space mean speed, the traffic density at the merge and diverge could then be subsequently calculated. Lastly, lane changes were counted manually from video recordings. The weaving section is divided into four segments (the segment lengths are a result of how the weaving section is covered by different camera recordings). Lane change activities are counted in segment 1, 2, and 3. Segment 0 is under the bridge and is difficult to observe. Also, there are not much lane change activities over this short segment. Hence, lane change activities are not counted for this short segment. It should be noted that a lane change event is counted whenever the vehicle makes clear intention to change lane with more than a quarter of the vehicle over the division line. The travel distance for the vehicle to finish the lane change will depend on the traffic condition, and is not considered in our study. The 3-hour period is divided into 18 10-minute intervals. Due to the costs of manual counting, lane changes were counted for the first 2 minutes of each 10-minute interval. The lane changing rate was assumed to be constant during each 10-minute interval. Figure 4 summarizes the site configuration and the data extraction with a schematic illustration.

Figure 2 Installation of Cameras at Winterthur Nord/Wülflingen..

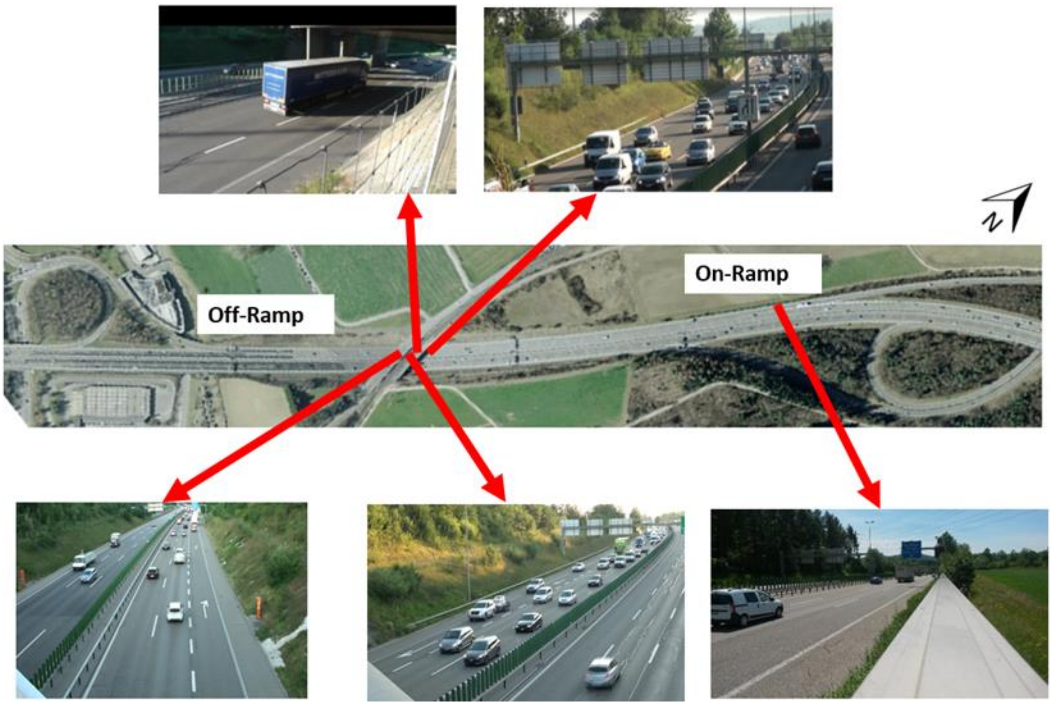


Figure 3 Installation of radars at Winterthur Nord/Wülflingen.

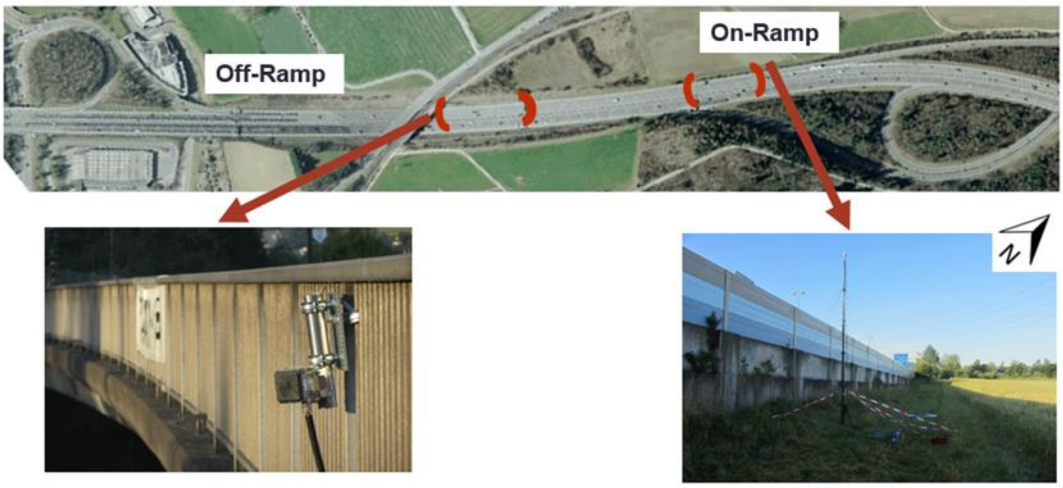
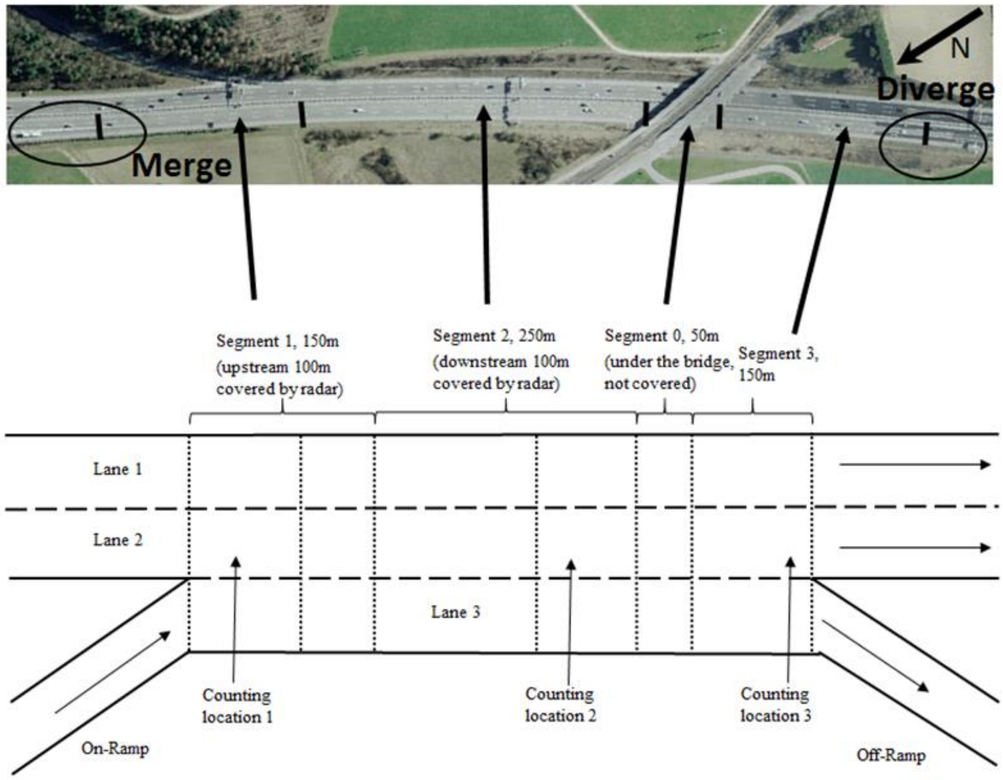


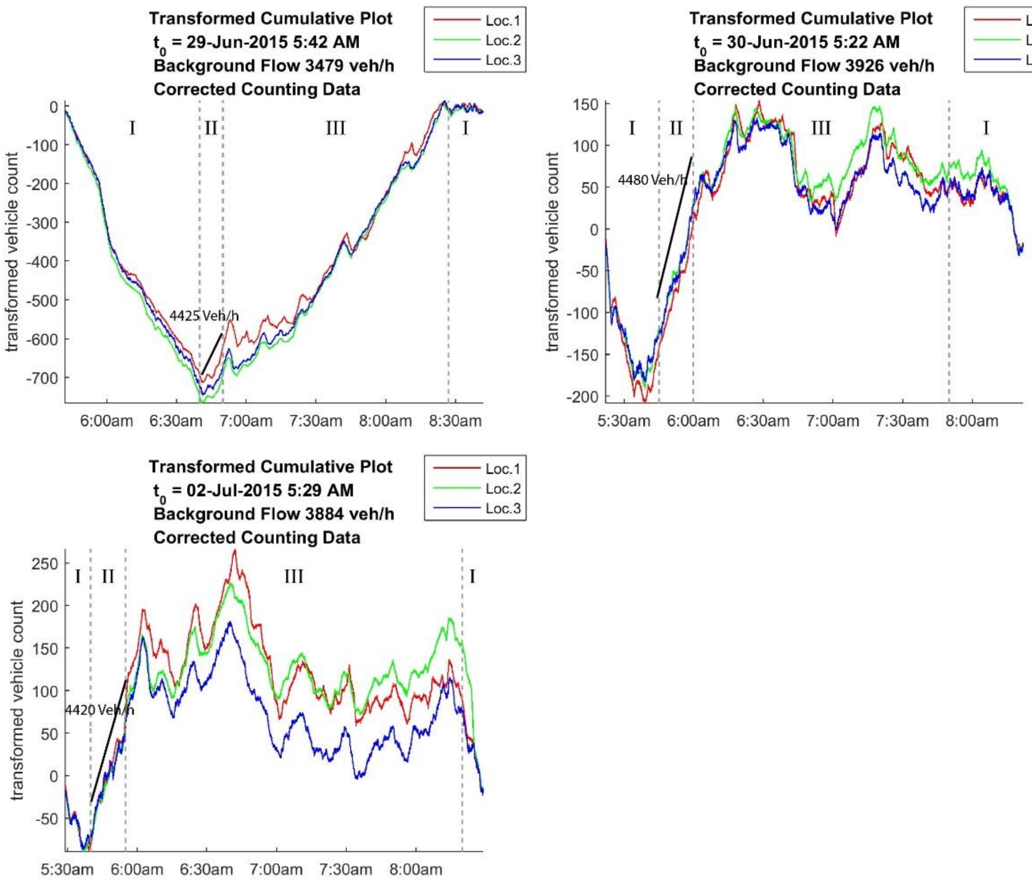
Figure 4 Aerial map (Google maps) and schematic illustration of the weaving section.



2.3 Traffic analysis

To analyze the flow and congestion of the weaving section. The transformed cumulative plots for the three locations are drawn for each of the three days in Figure 5. The transformed cumulative plot is the cumulative number of vehicles at the counting lo-cation minus a background flow (which in our case is set as the average flow during the 3-hour period). The purpose is to visually exaggerate the changes in flows to identify the capacity condition. It should be noted that due to the large volume of vehicles counted, a small counting error (0.5%) could lead to mismatch of counting results from the three locations. To amend this, miss-counted cars are added proportional to the flow to make the total number of vehicles equal at the three counting locations. This results in some crossover of the lines and makes the identification of the exact start and end of the capacity conditions difficult. Therefore, the traffic conditions were determined with the help of video recordings and traffic measurements from the radars. However, the capacity value calculated from the counting data should have only a small error (0.5%).

Figure 5 Transformed cumulative plots.

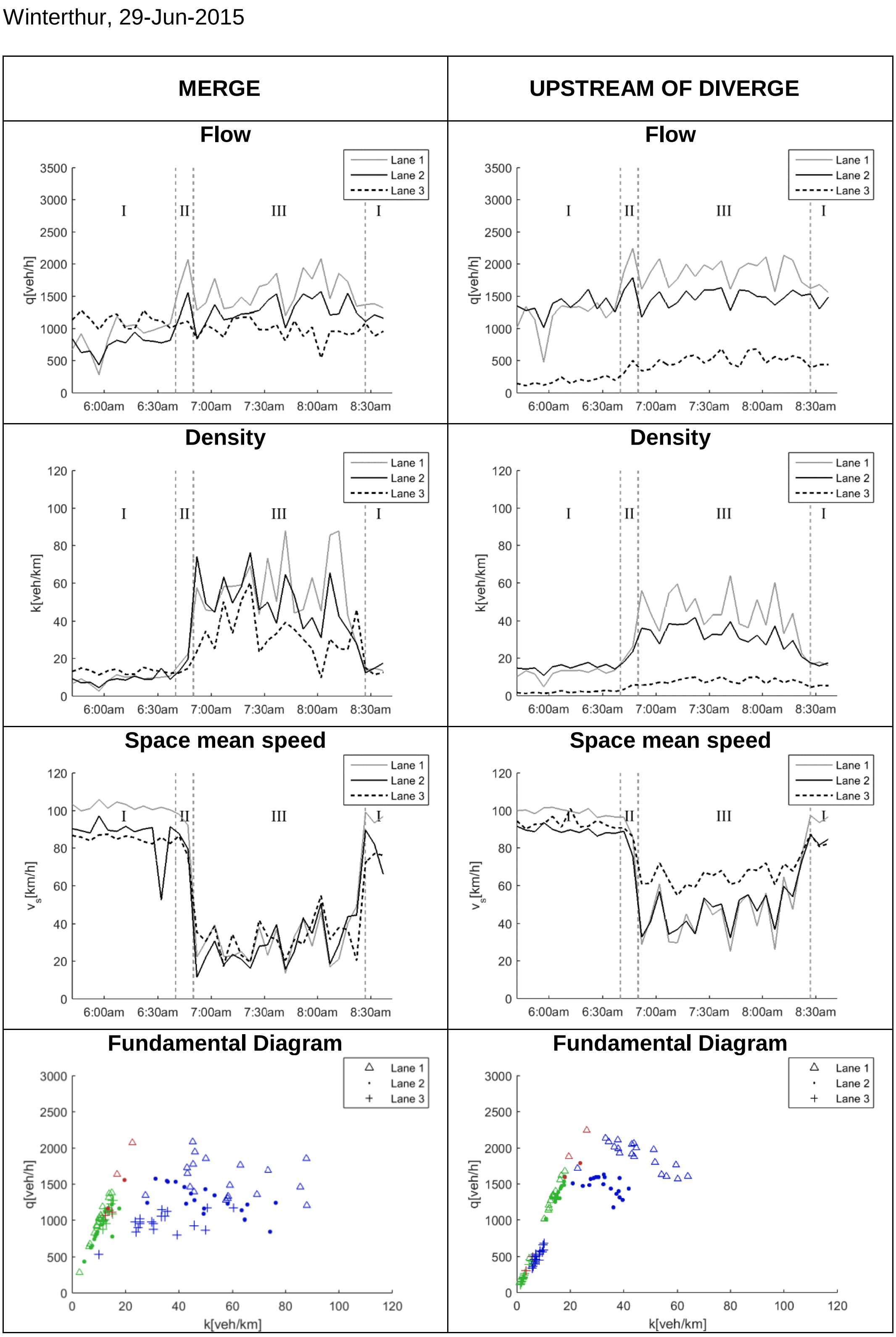


The measured period is divided into three sets of traffic conditions. At the beginning, the traffic is uncongested because the traffic volume is low. This uncongested traffic state is denoted as state I. When the traffic volume increases, the weaving section bottleneck is activated and the weaving section is discharging at capacity. The bottleneck is identified to be at the beginning of the weaving section. This phase with an active weaving bottleneck is denoted as state II. When the traffic volume increases further, congestion starts to form downstream of the weaving section and eventually spills back into the weaving section. This causes a period of severe congestion within the weaving section, when the cars make stop-and-go movements. This phase with downstream congestion is denoted as state III. When the demand decreases after the peak period, the congestion gradually dissipates and eventually the traffic returns to the uncongested state, i.e. state I.

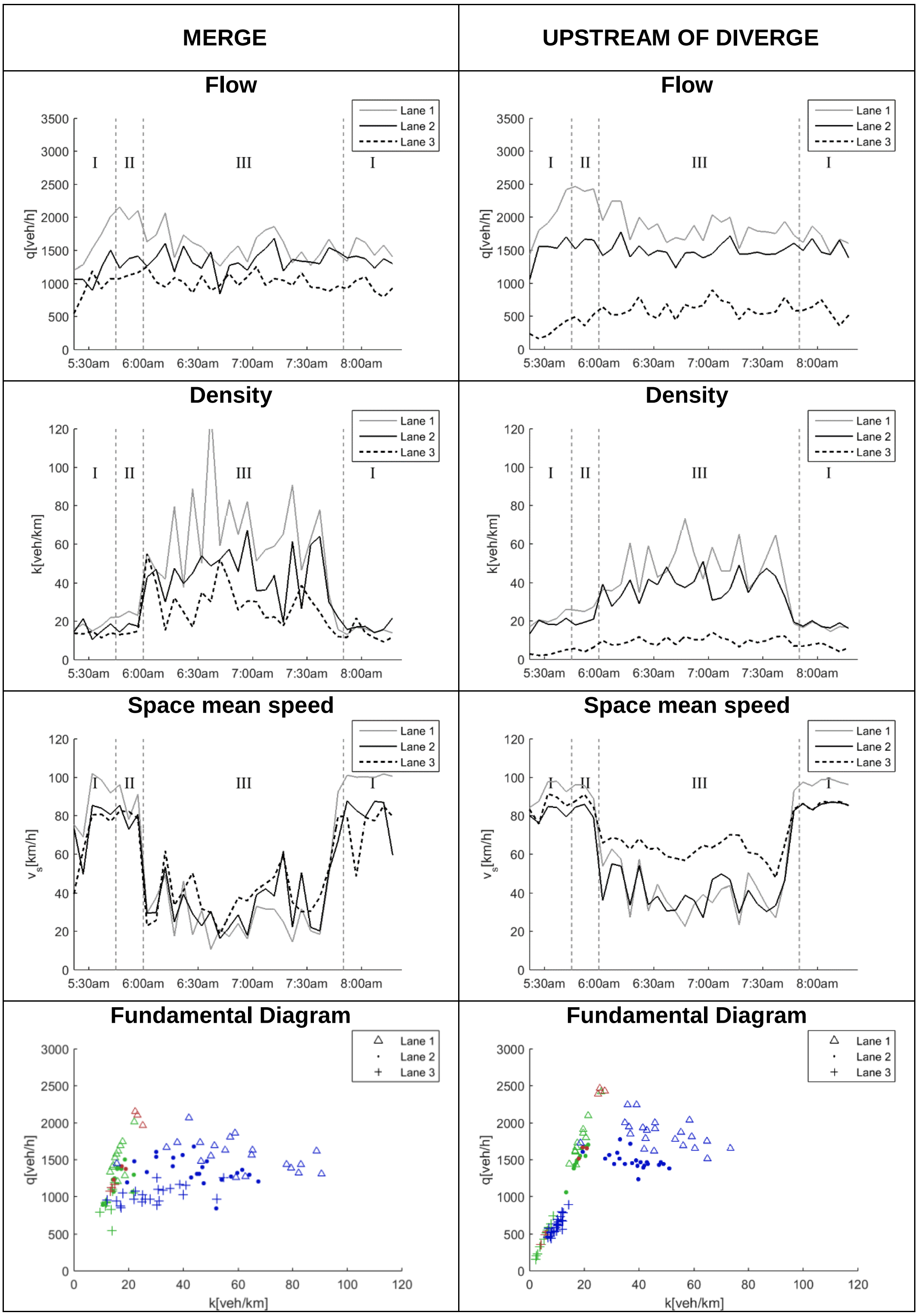
The capacity of the weaving section is calculated from the average dis-charge rate of the intermediate counting location during the period with an active weaving bottlenecks (i.e. state II). The capacities for each of the three days are determined to be 4425veh/h, 4480veh/h and 4420veh/h. The average capacity is 4442veh/h, with just a very slight variation across the three days.

The flow time series, density time series, the speed time series, and the fundamental diagrams of counting location 1 (merge) and counting location 2 (upstream of diverge) are summarized in Figure 6. The plots are made on a per-lane basis for each of the three days. 5-minute average is used to smooth out temporary fluctuations. For the fundamental diagram, points are colored according to the traffic states. Green, red and blue are respectively the free-flow state (state I), the state with an active weaving bottleneck (state II), and the state with downstream congestion (state III). In addition, the free-flow speed for each lane is calculated by a least square linear regression for the points belonging to state I. The calculated free-flow speeds and the qualities of the fit (R^2 values) are summarized in Table 1.

Figure 6 Traffic characteristics at counting location 1 (merge) and counting location 3 (diverge).



Winterthur, 30-Jun-2015



Winterthur, 02-Jul-2015

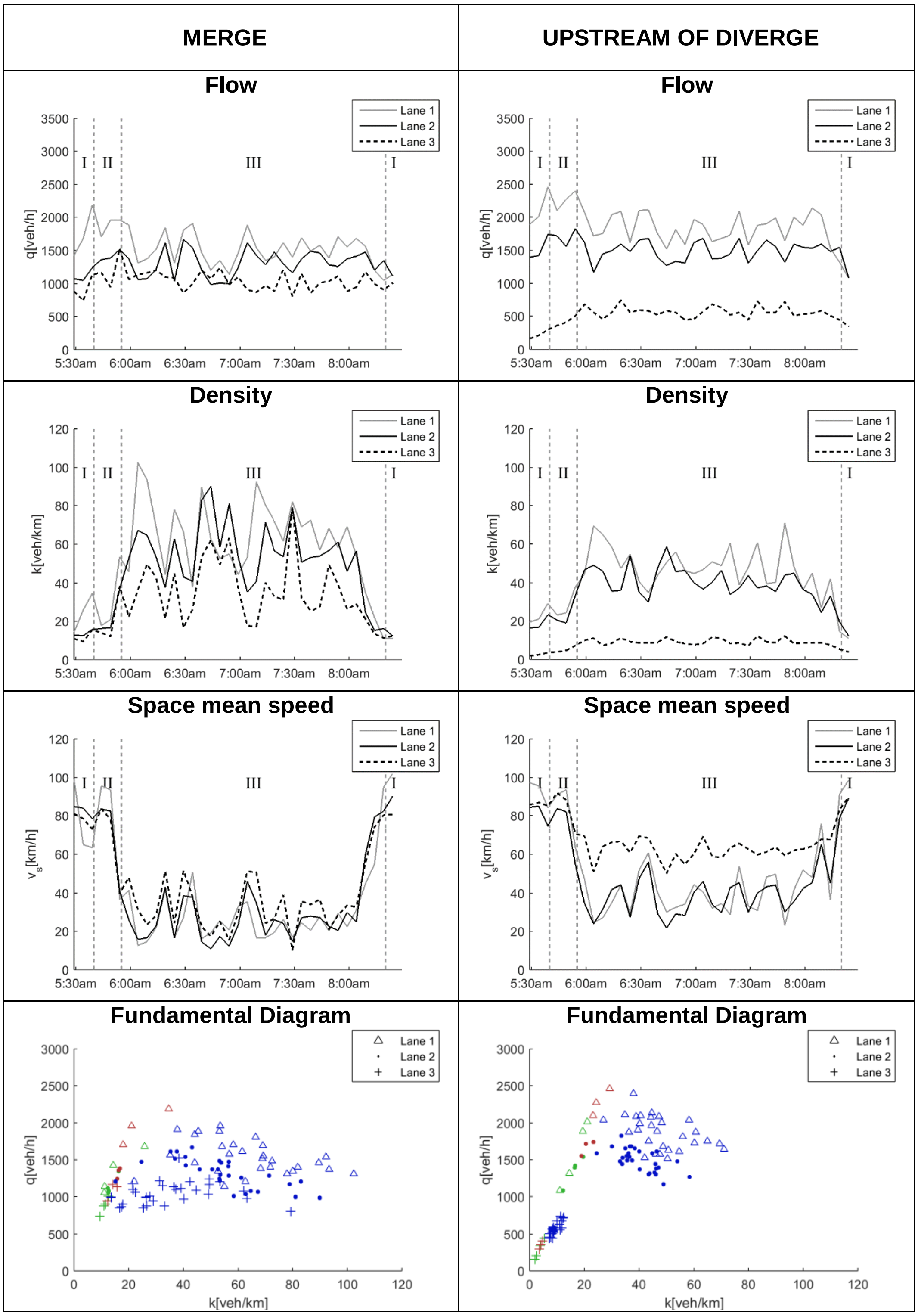


Table 1 Free flow speeds and qualities of the fit (R^2 values).

29.06.15		Free flow speed (km/h)	R^2 value of the regression
Counting location 1	Lane 1	99.0	0.9989
	Lane 2	79.1	0.9704
	Lane 3	83.1	0.9971
Counting location 2	Lane 1	97.9	0.9994
	Lane 2	88.1	0.9991
	Lane 3	86.8	0.9961

30.06.15		Free flow speed (km/h)	R^2 value of the regression
Counting location 1	Lane 1	93.2	0.9852
	Lane 2	74.3	0.9673
	Lane 3	67.3	0.9489
Counting location 2	Lane 1	94.6	0.9978
	Lane 2	83.3	0.9982
	Lane 3	85.9	0.9993

02.07.15		Free flow speed (km/h)	R^2 value of the regression
Counting location 1	Lane 1	78.6	0.9571
	Lane 2	84.8	0.9988
	Lane 3	80.2	0.9998
Counting location 2	Lane 1	95.6	0.9994
	Lane 2	83.2	0.9981
	Lane 3	85.6	0.9988

Looking at the density, it is observed that, both at the merge and upstream of diverge, density is generally highest on lane 1. This indicates a significant number of vehicles have already changed to lane 1 before entering the weaving section, either to avoid weaving vehicles or to make space for them. These vehicles remain on lane 1 along the entire weaving section. The density on lane 3 is generally lower. A possible explanation is the much lower F-R flow on this site. Therefore, when gaps are created on lane 3 when vehicles change from lane 3 to lane 2, there are not sufficient vehicles changing from lane 2 to lane 3 to fill these gaps. This process results in a lower density on lane 3. One would expect the density on lane 3 to decrease further downstream of the weaving section, which is indeed observed from density upstream of the diverge.

Looking at the speed, it is observed that there is in general a higher speed on lane 1 than on lane 2 both at the merge and upstream of the diverge, except during downstream congestion. Also, the speeds on all three lanes are significantly reduced at the merge. All these observations confirm our assumption that intensive lane change activities reduce speeds and most lane changes happen at the merge. Note that the vehicle speeds on lane 3 upstream of the diverge are slightly affected by downstream congestion. This suggests that at counting location 2, not all F-R and R-F vehicles have finished the lane changing maneuvers. Hence, vehicles on lane 3 still interact a little with vehicles on lane 2. One would expect downstream congestion would have less impact further downstream the weaving section.

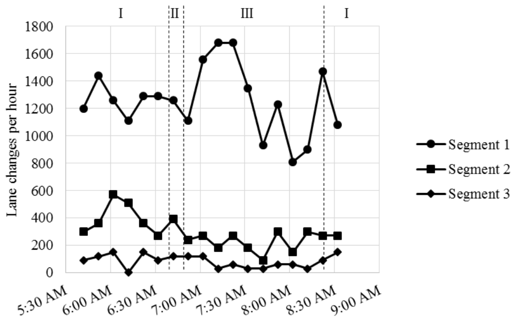
Looking at the flow, as a result of the higher density and higher speed on lane 1, the flow on lane 1 is generally the highest both at the merge and the diverge. Lane 3 generally has the lowest flow, especially upstream of the diverge, because there are not many weaving vehicles.

The fundamental diagrams of the merge and the diverge look very different. Firstly, for all three lanes, the points (red) corresponding to the active weaving bottleneck states mostly lie around the free flow region both at the merge and upstream of the diverge. However, the capacity of lane 1 and lane 2 are lower at the merge. (Capacity of lane 3 upstream of the diverge cannot be observed and compared.) This indicates that the weaving section bottleneck is at the merge. Secondly, for lane 2 and lane 3 at the merge, there are a lot of points lying below the free flow state (green) points, especially around the capacity region. Graphically, the fundamental diagram at lane 2 and lane 3 are better defined upstream of the diverge, where at the merge it is a smear of points, especially around capacity. This confirms our assumption that the capacity of the weaving section depends on the intensity of the lane change activities, and hence the mix of the flows. Thirdly, looking at the free flow region and the free flow speeds in Table 1, one would infer the drivers do not actively decelerate when entering the weaving section. For the lanes and dates with well-defined free flow speeds (i.e. a good quality of fit), there does not seem to be a significant difference between the merge and upstream of diverge. However, the fits upstream the diverge are better than the fits at the merge. This indicates that even at free flow state, the speeds at the merge are often affected and reduced by the lane change activities.

Figure 7 shows detailed time series information of the spatial distribution of the lane changes across the weaving section for each of the three days. A summary for the three days is also included.

Figure 7 Lane change spatial distribution across weaving section.

29.06.15



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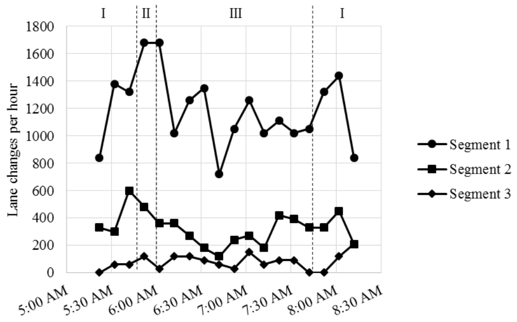

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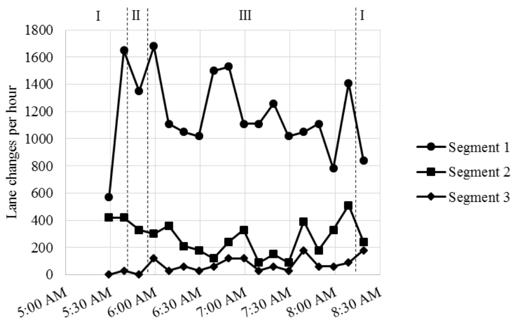
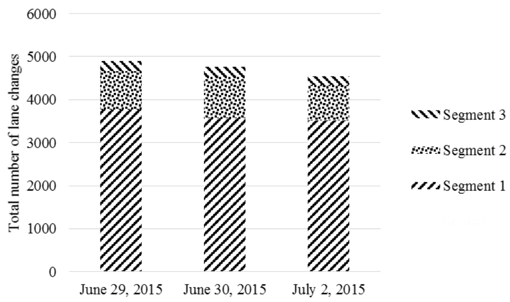


Summary



It could be seen from Figure 7 that on all days the majority of the lane changes happen at the merge (segment 1), while there are not many lane changes at the diverge (segment 4). This is true during all time periods and under all traffic conditions. It should be noted that the length of segment 1 is only 150 meters, which is only 25% of the weaving section. Therefore, about 80% of the total lane changes happen within 25% of the weaving section length. To make the comparison more consistent across the different segments (which are of different lengths), the lane change rate per meter is summarized in Figure 8 for each of the three days.

Figure 8 Lane changes per-meter in different segments across the weaving section.

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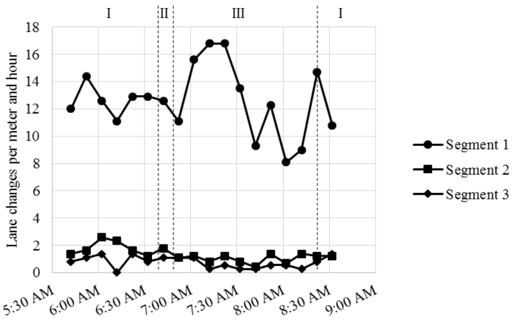

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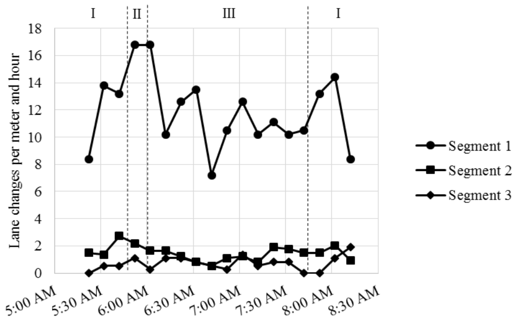

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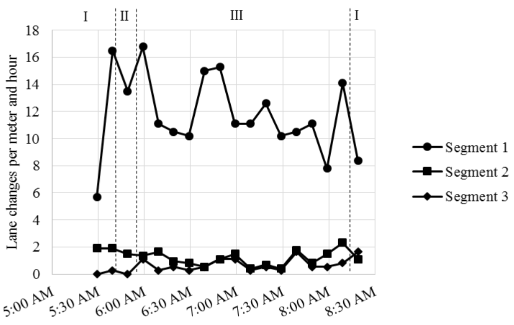
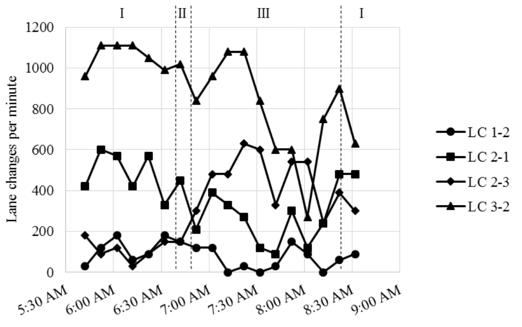


It could be seen from Figure 8 that, there are intensive lane changing activities at the merge. On the other hand, there are not many lane changes at the diverge of the weaving section, so likely it operates like a normal highway segment. This confirms our previous assumption that the intensive lane changing activities at the merge could have reduced the vehicle speeds and density, which activates the bottleneck around the merge location.

Figure 9 shows detailed time series information of the lane change type distribution for each of the three days. A summary for the three days is also included.

Figure 9 Lane change type distribution.

29.06.15



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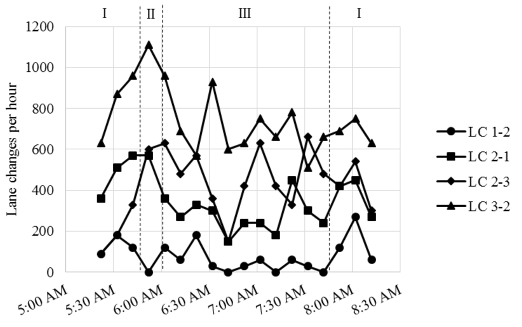

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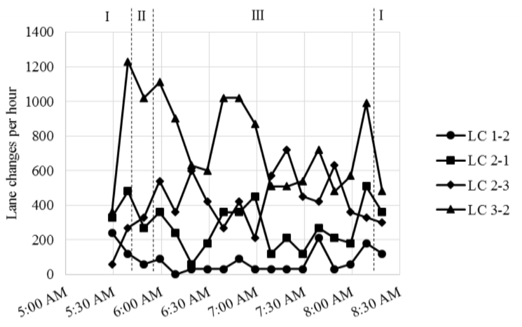
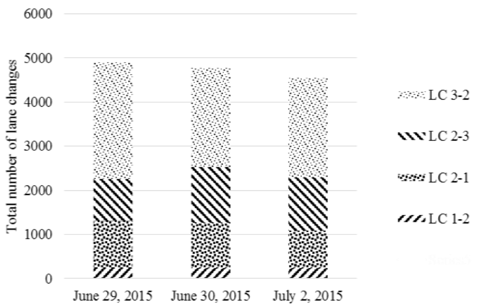


Summary

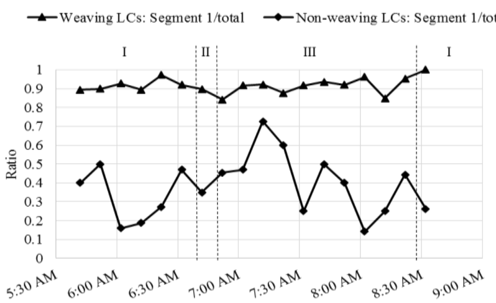


It could be seen from Figure 9 that, on all three days most lane changes are weaving lane changes (i.e. lane change 2-3 and 3-2), while there are not many non-weaving lane changes (i.e. lane change 1-2 and 2-1). This is true during all time periods and under all traffic conditions. The percentage of weaving lane changes and non-weaving lane changes in the merge segment is plotted for each of the three days in Figure 10.

From Figure 10 we see that about 90% of the total weaving lane changes happen in the merge segment, while about 35% of the total non-weaving lane changes happen in the merge segment. This is generally true during all time periods and under all traffic condi-tions. Note that, the merge segment is only about 25% of the total weaving section length, so the absolute majority of the weaving lane changes are happening around the merge. Although only about 35% of non-weaving lane changes happen in the merge segment, it is still higher than expected from a normal highway segment where the distribution is uniform. This shows that weaving lane changes could have triggered extra non-weaving lane changes, in addition to those already finished before the start of the weaving section.

Figure 10 Percentage of weaving and non-weaving lane changes at the merge.

29.06.15



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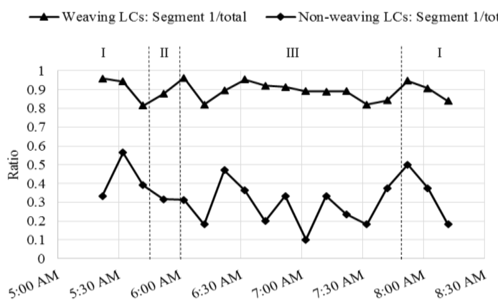

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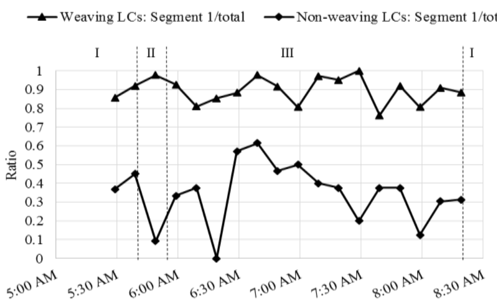


In summary, analysis of this weaving section confirms that the early lane change behavior in weaving sections is a general Swiss driving behavior. Most weaving vehicles make the lane changes immediately after the security line at the merge. A significant number of vehicles change to the over-taking lane before entering the weaving section hence the majority of the non-weaving lane changes are already finished upstream of the weaving section. The bottleneck of the weaving section is near the merge location and is activated when there is intensive lane changing activities. When the bottleneck is activated, the speeds of the vehicles are reduced near the merge location, which would lower the Level of Service of the road section.

3. Weaving area Rotkreuz/Ruetihof (180m)

3.1 Site description

This A0 highway weaving site is located near Rotkreuz. It has two lanes, one through lane and one ramp lane. This site has an annual daily traffic volume of about 17000 vehicles per day. During the evening peak hours the flow could reach up to about 1600veh/h. This is within the capacity of the weaving section so a bottleneck almost never forms under normal conditions. The weaving section itself has a length of about 180m and the allowed speed limit is 80km/h. The ramp to freeway (R-F) demand is much higher than the freeway to ramp (F-R) demand.

3.2 Measurement and data description

The evening peak period was chosen for measurement for this site on 5 days (September 21st, September 24th, September 28th, October 5th, October 7st, and July 2nd). On each day, measurement was carried out for about 5 hours, but only 3 days were chosen for analysis. The days with the most normal circumstances are chosen. For each of the 3 days, about 3 hours of data were extracted. The demand is within capacity and the traffic is uncongested throughout the measurement period.

Four video cameras were installed. Two on tripods at the merge location and two on a bridge overlooking the downstream segment. Recordings and installation positions of them are illustrated in Figure 11. Two radars were installed to cover the merge area and the diverge area as illustrated in Figure 12. The radar at the merge was installed on a military mast. The radar at the diverge was installed on a bridge. Note that, since this weaving section is short, the two radars already cover the whole section, as illustrated by the brackets in the figure.

Three kinds of data were extracted from the measurement. Firstly, manual vehicle counting was made from the video recording at three locations along the weaving section: at the merge, diverge and in the middle of the weaving section. All counting data are available for each lane, and vehicles were classified into cars and trucks. The flow at the merge and diverge could then be calculated from the counting. Secondly, the speed of the vehicles was directly extracted from the radars. The speed of the detected vehicles at each location is assumed to be a sample estimate for the speed of all vehicles passing that location. An estimate for the space mean speed is calculated by taking the harmonic mean of the speeds of the detected vehicles. With both the flow and space mean speed, the traffic density at the merge and diverge could then be subsequently calculated. Lastly, lane changes were counted manually from video recordings. The weaving section is divided into three segments (the segment lengths are a result of how the weaving section is covered by different camera recordings). It should be noted that a lane change event is counted whenever the vehicle makes clear intention to change lane with more than a quarter of the vehicle over the division line. Since the weaving section is short, even when a vehicle start to make the lane change immediately after entering the section (i.e. past the security line), it might have travelled near the diverge location by the time it finishes the lane change. Since the traffic condition remains the same throughout the measurement period, and due to the costs of manual counting, lane changes were counted for only 30 minutes for each day, on a per minute basis.

Figure 11 Installation of Cameras at Rotkreuz/Ruetihof.

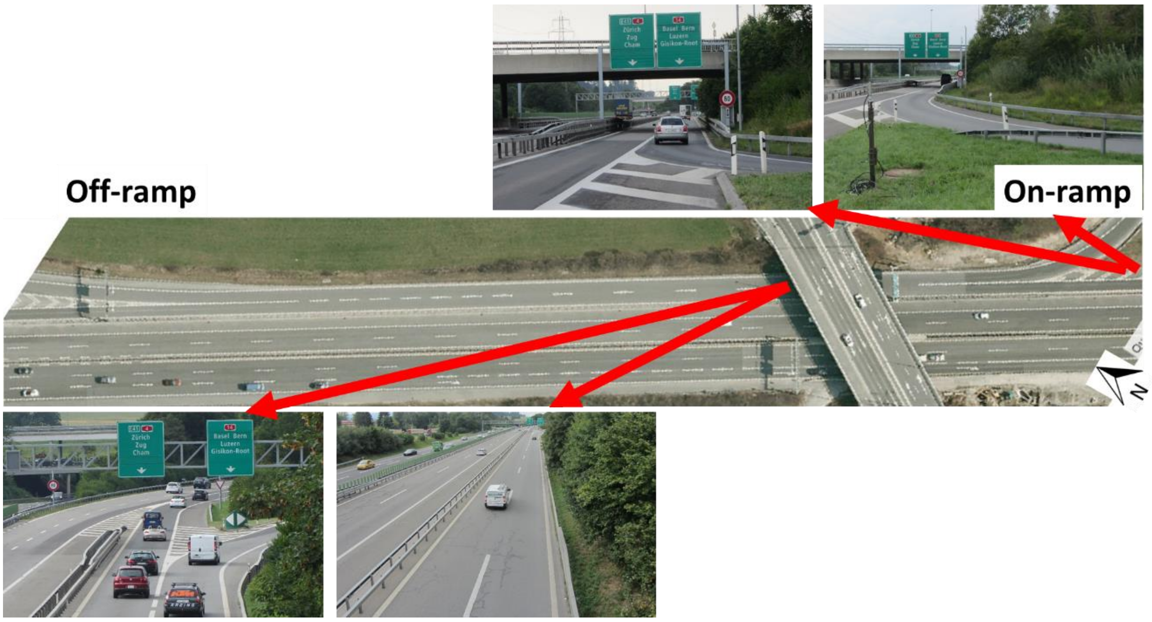
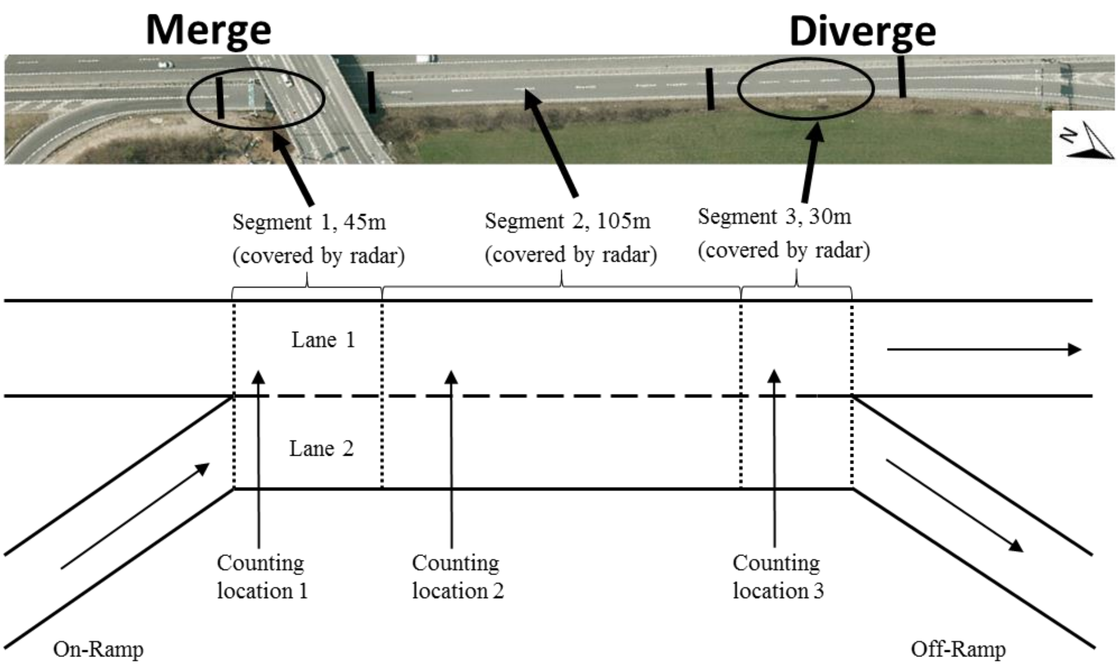


Figure 12 Installation of radars at Rotkreuz/Ruetihof.

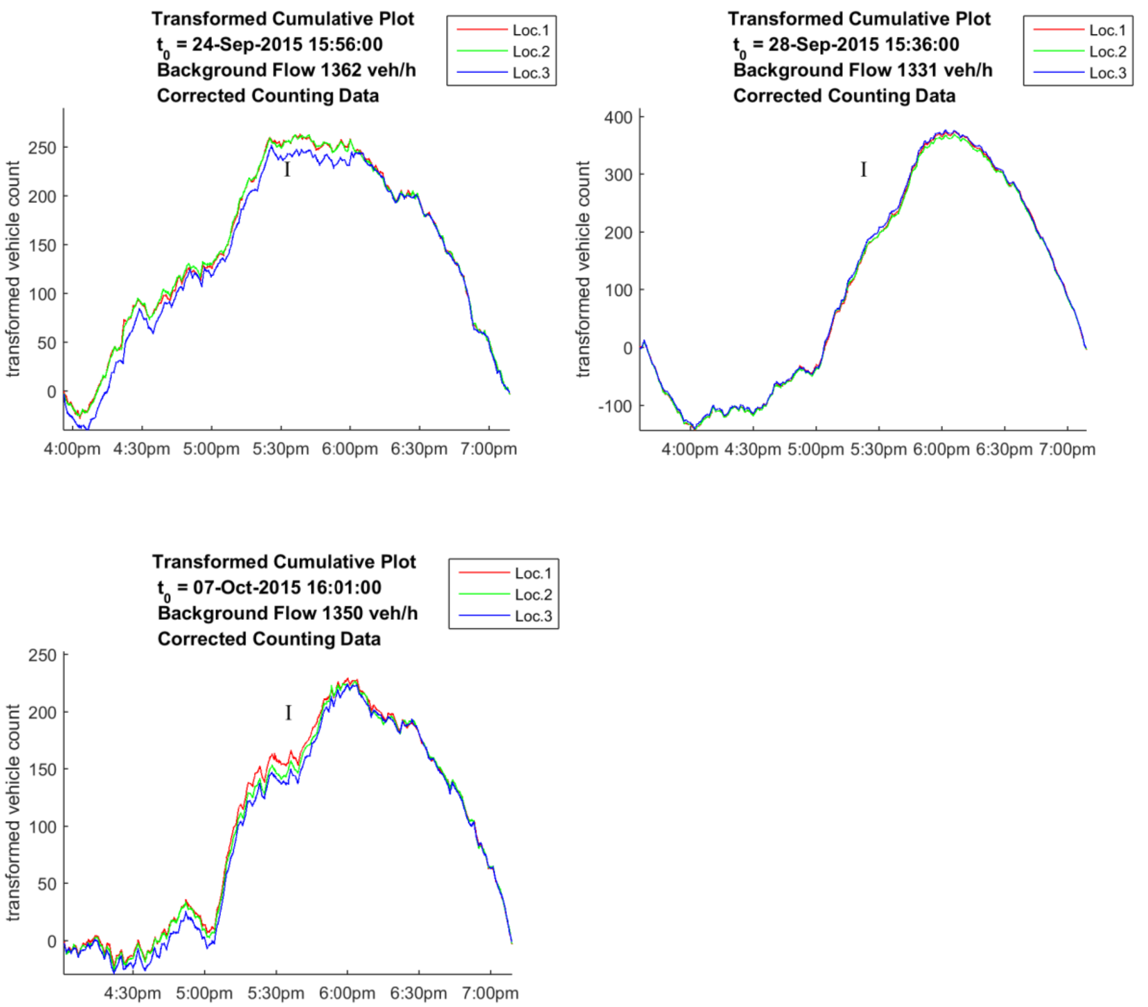
Figure 13 Aerial map (Google maps) and schematic illustration of the weaving section.



3.3 Traffic analysis

To analyze the flow and congestion of the weaving section. The transformed cumulative plots for the three locations are drawn for each of the three days in Figure 14. Processing of the transformed cumulative plots is as explained in Section 2.3. Note that the traffic is uncongested throughout the whole measurement, so the capacity of the weaving section could not be observed. During the peak periods, the highest flow observed is about 1800veh/h.

Figure 14 Transformed cumulative plots.



The flow time series, density time series, the speed time series, and the fundamental diagrams of counting location 1 (merge) and counting location 3 (diverge) are summarized in Figure 15. The plots are made on a per-lane basis for each of the three days. 5-minute average is used to smooth out temporary fluctuations. In addition, the free-flow speed for each lane is calculated by a least square linear regression for the entire measurement period. The calculated free-flow speeds and the qualities of the fit (R^2 values) are summarized in Table 2.

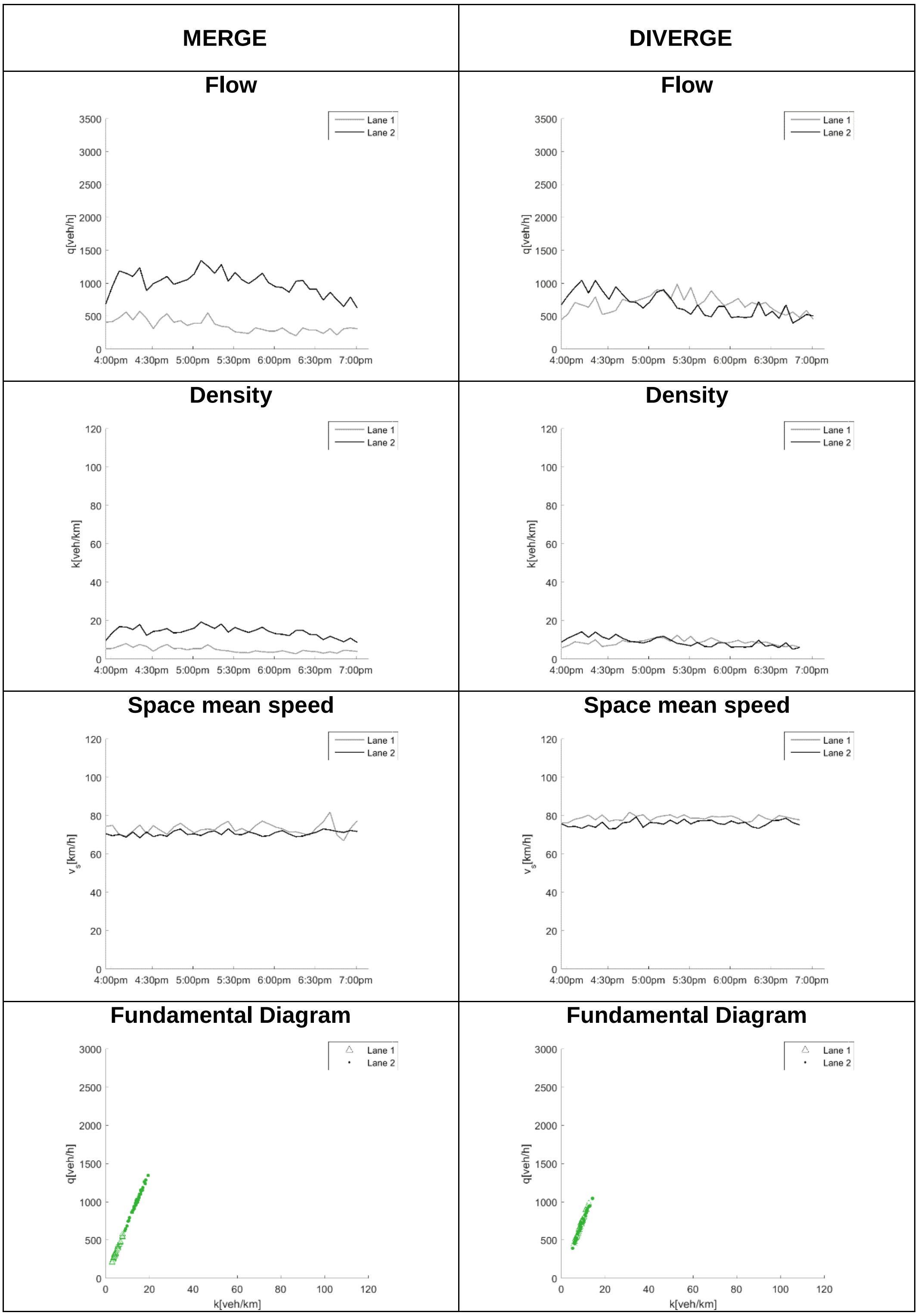
Looking at the density, it is observed that, density on lane 1 increases from the merge to the diverge, while the density on lane 2 decreases. This is because the R-F flow is much higher than the F-R flow, so more vehicles have entered than exited lane 1 along the weaving section.

Looking at the speed from Figure 15 and Table 1, it is observed that the speed on lane 1 and lane 2 are similar both at the merge and at the diverge. Also, the speeds on both lanes are slightly higher at the diverge than the merge. It is possible than the lane change activities at the merge reduce the speeds. The effect, however, is minor given the traffic demand is much lower than capacity. The traffic operates in a free-flow state, which is less sensitive to perturbation from lane changing vehicles.

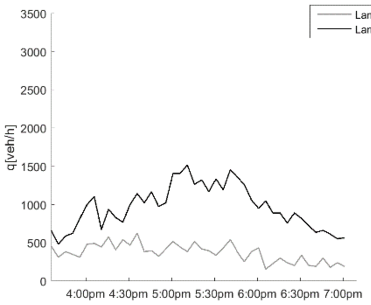
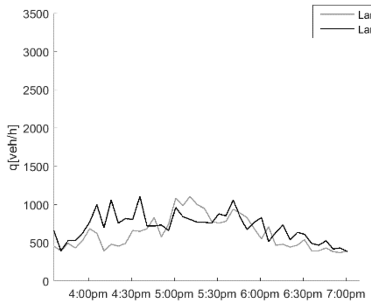
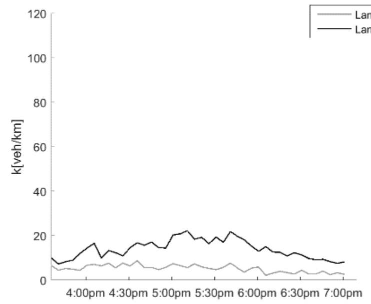
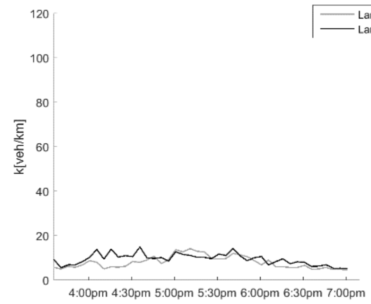
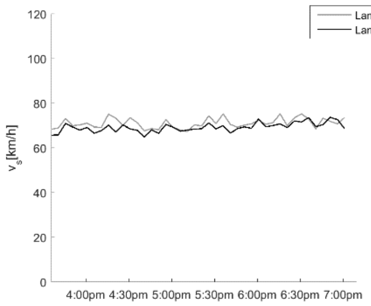
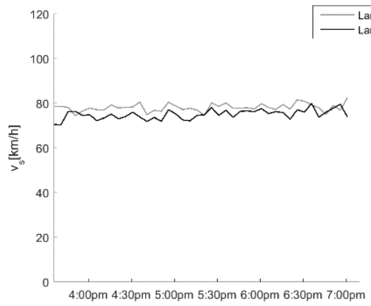
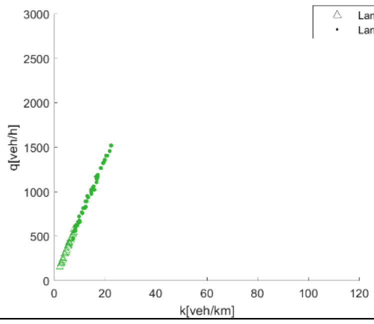
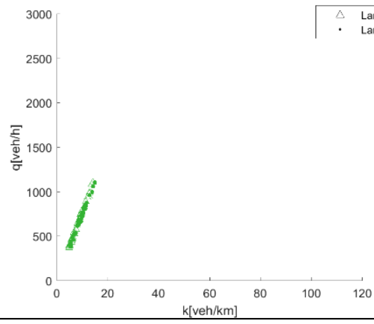
Looking at the flow, since it is much lower than capacity, it is mostly influenced by the density on each lane. As a result, flow on lane 1 increases from the merge to the diverge, while the flow on lane 2 decreases. Moreover, the fundamental diagrams for both the merge and the diverge has only the free-flow part. The capacity region is not observed.

Figure 15 Traffic characteristics at counting location 1 (merge) and counting location 3 (diverge).

Rotkreuz, 24-Sep-2015



Rotkreuz, 28-Sep-2015

MERGE	DIVERGE
Flow 	**Flow** 
Density 	**Density** 
Space mean speed 	**Space mean speed** 
Fundamental Diagram 	**Fundamental Diagram** 

Rotkreuz, 7-Oct-2015

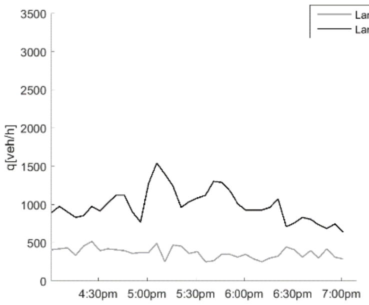
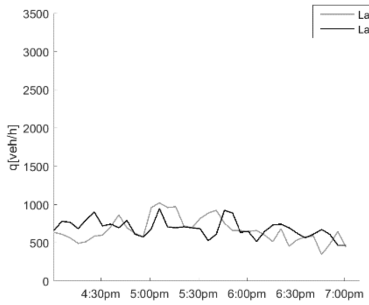
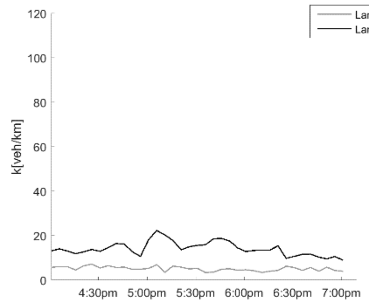
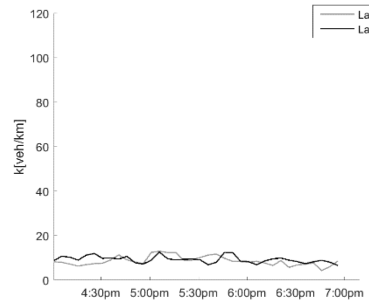
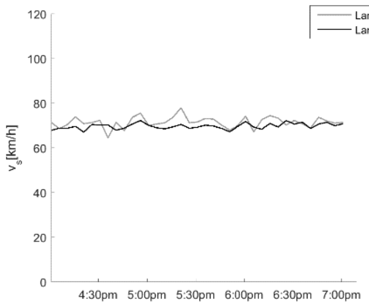
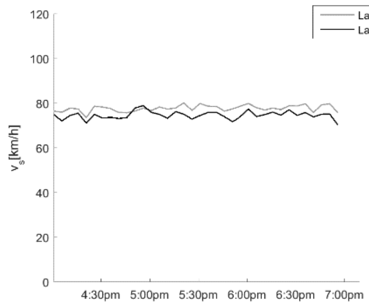
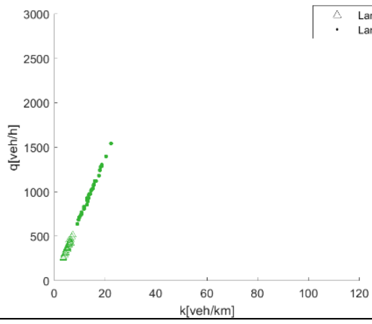
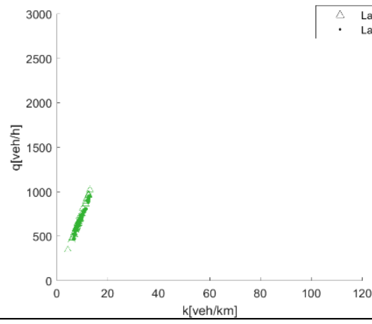
MERGE	DIVERGE
Flow 	**Flow** 
Density 	**Density** 
Space mean speed 	**Space mean speed** 
Fundamental Diagram 	**Fundamental Diagram** 

Table 2 Free flow speeds and qualities of the fit (R^2 values).

24.09.15		Free flow speed (km/h)	R^2 value of the regression
Counting location 1	Lane 1	72.9	0.9887
	Lane 2	70.6	0.9996
Counting location 3	Lane 1	79.0	0.9997
	Lane 2	75.6	0.9995

28.09.15		Free flow speed (km/h)	R^2 value of the regression
Counting location 1	Lane 1	71.0	0.9990
	Lane 2	68.9	0.9994
Counting location 3	Lane 1	78.0	0.9996
	Lane 2	74.7	0.9993

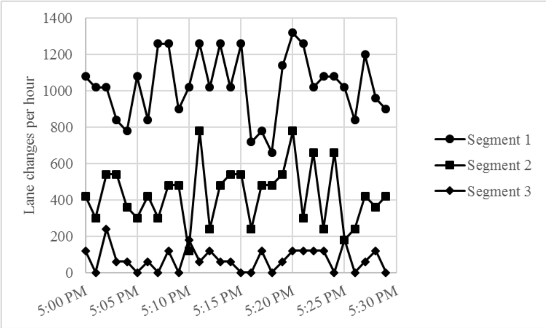
07.10.15		Free flow speed (km/h)	R^2 value of the regression
Counting location 1	Lane 1	71.3	0.9987
	Lane 2	69.6	0.9997
Counting location 3	Lane 1	77.7	0.9997
	Lane 2	74.5	0.9995

Figure 16 shows detailed time series information of the spatial distribution of the lane changes across the weaving section for each of the three days. A summary for the three days is also included.

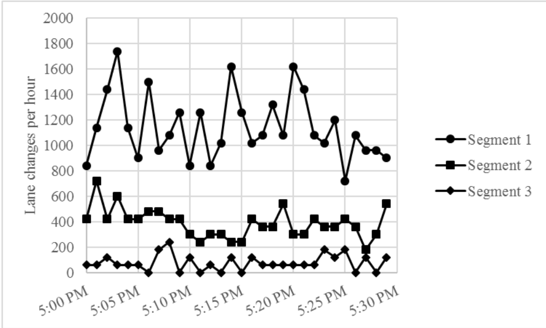
It could be seen from Figure 16 that on all days the majority of the lane changes happen at the merge (segment 1), while there are not many lane changes at the diverge (segment 3). This is particularly surprising the small weaving section length, and this is true during the entire extracted period. It should be noted that the length of segment 1 is 65 meters, which is only 31% of the weaving section. Therefore, about 70% of the total lane changes happen within 31% of the weaving section length.

Figure 16 Lane change spatial distribution across weaving section.

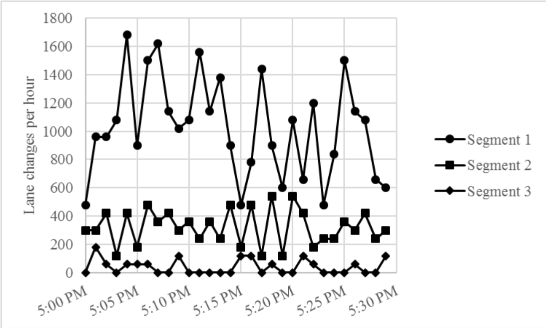
24.09.15



28.09.15



07.10.15



Summary

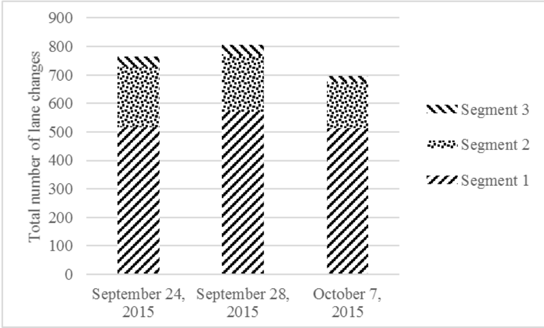
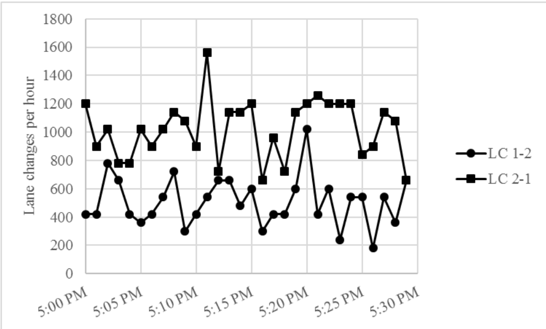


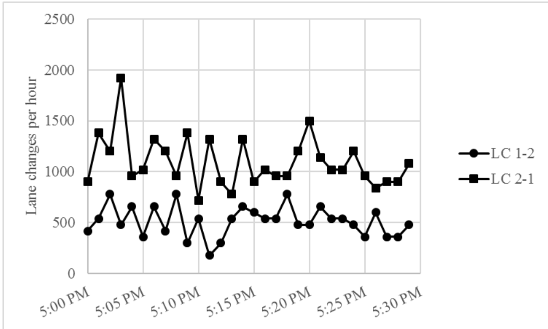
Figure 17 shows detailed time series information of the lane change type distribution for each of the three days. A summary for the three days is also included.

Figure 17 Lane change type distribution.

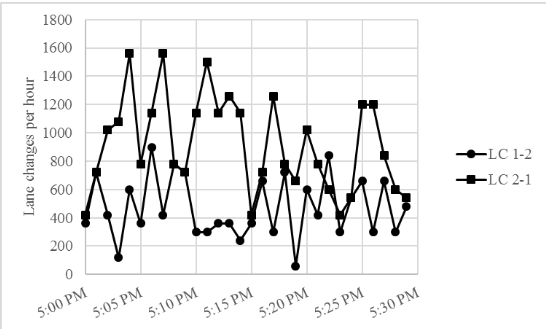
24.09.15



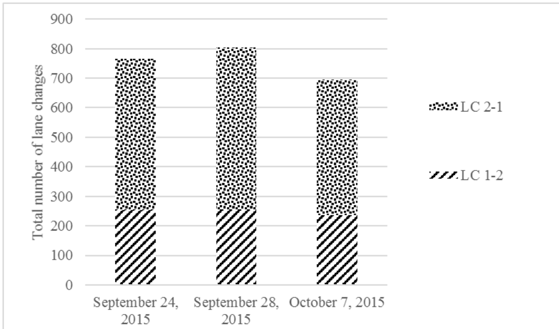
28.09.15



07.10.15



Summary



It could be seen from Figure 17 that, on all three days there are more vehicles changing into lane 1 than lane 2. This is true during all time periods and is due to higher R-F flow than F-R flow.

In summary, analysis of this weaving section confirms that the early lane change behavior in weaving sections is a general Swiss driving behavior. Most weaving vehicles make the lane changes immediately after the security line at the merge. This is true even for a short weaving section.

4. Conclusions

A descriptive analysis of the distribution and impacts of lane changes is presented in this paper. The main findings of this paper are the following.

- For the longer B0 type weaving section (570m), 70% of the total lane changes happen within the first 19% (100m) of the weaving section length during all time periods and under all traffic conditions. This includes 80% of the weaving lane changes and 30% of the non-weaving lane changes.

- For the shorter A0 type weaving section (180m), 70% of the total lane changes happen within the first 31% of the weaving section length.

- The speed is generally lower at the merge than at the diverge due to intensive lane change activities.

- A reduction of capacity of the main lane and the ramp lane at the merge compared to the diverge is the likely cause of the weaving section bottleneck. The reduction of capacity is likely due to the intensive weaving lane changing activity at the merge.

Since most of the lane changes take place at the merge of the weaving section despite varying weaving section lengths, the traffic at the merge location determines the capacity and operation of the weaving section. This suggests that the length of the weaving section has limited influence on the capacity and operation of the freeway weaving section.