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BCs Thesis

Effects of freeway traffic homogeneity on lane changing activity: The role of dynamic speed limits

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Zürich, July 2014

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Abstract

The objective of this thesis is to understand the influence of dynamic speed limits on flow rates and lane changing activity through empirical data recorded in a highway entering Barcelona. The thesis also aims to establish a better understanding of highway homogenization across lanes due to different speed limits. To that end, data of three different days under different speed limit conditions will be examined by looking at standard traffic diagrams and using various traffic tools, such as the identification of congested states and the definition of stationary periods.

The main conclusions are that variable speed limits do not modify the highway capacity, but the critical occupancy, by shifting it to significantly higher occupancy rates. This contradicts previous research and shows the misuse of dynamic speed limits for mainline metering. Additionally, lane changing activity has been proved to be extremely high during congestion. However, the analyzed data does not allow an exhaustive understanding of lane changing activity for congested conditions. For uncongested states a relation between occupancy and lane changing rates has been assessed.

Finally it motivates further research in these subjects.

Part I. Introduction and technical basis

1. Dynamic speed limits (DSL)

1.1 Introduction

In a globalized world where distance has lost its importance, people are used to travel. In the last decades there has been an increase in car use. But as we cannot constantly adapt our infrastructures to the demand for both economic and environmental reasons, we need to find a way where we can improve traffic in a faster and more efficient way. This can be called traffic management. The first goal of traffic management is to increase the capacity of highways. The aspiration is to achieve more flexibility in the use of the existing highways.

One of these active traffic management strategies is variable or dynamic speed limits (VSL or DSL). Nowadays, in many places DSL are used. Their goal is to limit road traffic speed in real time, to adapt to different situations: weather, accidents, bottlenecks, etc. It is claimed that they help to reduce pollution and accident rates by homogenization of the road. The term "homogenization" refers to reduction of variance in speed, occupancy or/and lane changes. Another possible function of DSL is the prevention of traffic breakdown by avoidance of too high densities. Nevertheless we do not know yet the exactly influence of DSL in traffic and its fundamental diagram (FD) **Figure 1**.

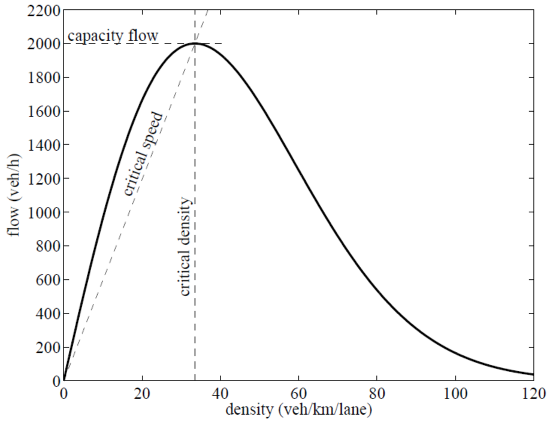

Figure 1 – Theoretical FD with labeled characteristics (Hegyi, 2004)

Variable speed signs (VSS) were first introduced in Germany in the early 1970s and some years after in the Netherlands. Since then, the introduction of DSL has expanded rapidly worldwide. The reason for this is probably the low implementation costs. However, few empirical studies from roads with DSL have been done and the conclusions of these studies in different countries seem not to agree. Some of them concluded that the data analysis was not conclusive, because DSL benefits are originated in microscopic traffic and it is only possible to evaluate them using microscopic data. Only a smart use of aggregations could help to understand or to see some relationship or phenomena.

There is a difficulty to analyze real data of sections with dynamic speed limits. One of the reasons is that the VSS use complex algorithms controlled by traffic management institutions of the area. But, as concluded in a recent PhD Thesis (Torné, 2013), it is necessary to do more analyses of real data. In fact, the best scenario situation would be to have micro data from a freeway stretch where we know the criteria of the variable speed signs.

1.2 Previous research

Hitherto empirical studies have only assessed aggregated traffic flow. This section tries to sum up in a simple way all conclusions and opinions originated by previous research.

Dynamic speed limits are good to remind of the speed limits, thereby speed infractions are reduced and consequently the rate of accidents. Using driving simulators it has been shown that DSL increase the homogeneity of driving speeds (Van Nes & et al, 2010). The harmonization across lanes is expected to improve drivers comfort and to reduce stop-and-go traffic situations. It is claimed that DSL stabilize traffic flow, because homogenizing the speeds across lanes would reduce lane changes, leading to an increase of flow. This homogenization approach of DSL typically uses speed limits over the critical speed to avoid reducing the capacity.

Besides the speed harmonization, the most extended and stated affirmation about DSL is that they increase traffic safety. During the last years a lot of studies have stated that variable speed limits reduce accident probability in 20% to 30% (Papageorgiou & Kosmatopoulos, 2008). More recent analysis (with VISSIM simulations) affirm that DSL reduce the lane changing rate and the number of stops (Wang, 2011). Though, this last statement has not been contrasted with empirical data yet.

Earlier researches in Germany suggested that at high traffic volumes the stabilizing effect of reducing variances of speeds would increase the mean speed and lead to an augmentation of flow rates. These increments should be around 5% to 10% (Zackor, 1972). Later Cremer proposed model where the fundamental diagram would depend on the ratio of the DSL and the free-flow speed without limit (b), **Figure 2** (Cremer, 1979). Note that b=1 means that DSL is the same as the free-flow speed, but it is used to represent FD without DSL.

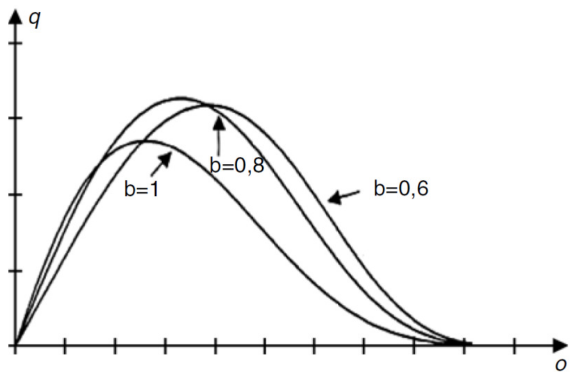

Figure 2 – Cremer quantitative model for FD with DSL

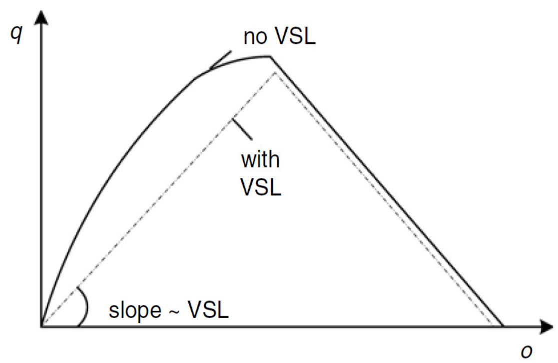

Figure 3 – Hegyi model for FD with DSL

More recent investigations (Hegyi, 2004) point out that DSL only replace the under-critical part of the FD by a straight line with constant slope, corresponding to the VSS. **Figure 3**.

The first analysis of empirical data (Papageorgiou & Kosmatopoulos, 2008) recalls that there is no consensus about how DSL really affect traffic flow. In that investigation it was shown that the DSL-affected fundamental diagram shifts the critical occupancy to higher values, crossing the no-VSL curve. This cross points were slightly beyond the initial critical occupancy. It also concluded that the possible capacity increase or decrease could not be ensured. The capacity and critical speed could change up to 10% from day to day due to stochastic effects without DSL.

The other mentioned approach of DSL is to prevent traffic breakdown. In this case, the speed limits showed in VSS are clearly lower than the critical speed aiming that this operation may limit the flow. It is also claimed that besides this two big approaches, DSL may be also useful to prevent sudden shock waves (Hegyi, 2004).

2. Research objectives

Previous scientific researches (Menendez & Daganzo, 2007) (Cassidy, Jang, & Daganzo, The smoothing effect of carpool lanes on freeway bottleneck, 2010), show that a diminution in the number of lane changes, due to HOV lanes directly upstream of a bottleneck, cause an increase in the discharge rate. These assertion open a new possibility to DSL. It can be expected that any strategy that reduces the lane changing activity, may increase flow rates.

In another hand, intuition indicates that homogeneous traffic in a highway would reduce lane changes, but this affirmation has not been quantified so far. As it has been explained in the last chapter, DSL are thought to homogenize traffic in highways. In the extent of understanding the fundamental effects of dynamic speed limits in a freeway traffic flow, detailed data is necessary. Nevertheless, up to now only the macroscopic influence of the DSL (aggregated traffic) has been assessed, for this reason it is difficult to evaluate the homogenization of the highway.

Few empirical studies of the impact of DSL on aggregated traffic flow have been carried out. More research is necessary in order to extract conclusive results of the expected reduction of lane changes and the increasing capacity due to dynamic speed limits strategies. In this thesis, macro behavior of cars is deeply examined and fundamental variables of traffic between adjacent lanes are compared, in the hope that it can clear up how DSL influence traffic homogeneity and other traffic characteristics.

Figure 4 depicts the relations that must still be proven in order to directly relate dynamic speed limits to higher capacities of highways. This relation would be an interesting subject to study in order to improve traffic conditions in a fast and economic way.

Figure 4 – Conceptual scheme

In the interest of filling this gap in research this Bachelor Thesis will carry on an analysis of the data from an experiment (Soriguera & Sala, 2013) done in a highway provided with VSS, that enters Barcelona. The aim of this analysis is to explain the effect of dynamic speed limits, both on the prevention of traffic breakdown (and reduction of flow at under-critical speed limits) and on the effect of homogenization, and how this supposed homogenization influences the rate of lane changes, by deeply studying a particular section of the highway. Thereby it is expected that the results of this investigation will help to the efficient use of DSL technology.

Part II. Freeway lab B-23

3. Introduction

The experiment was carried out in June 2013 in the highway B-23, located in the west side of Barcelona, during 7 days. The experiment consisted on changing the DSL in the southbound direction, entering Barcelona, and collecting all the data obtained from all the detectors situated along the 13,15km stretch. As the obtained data is very detailed and some of it also has individual vehicle data it is possible to evaluate the homogeneity of the highway.

Figure 5 – Situation map of B-23 (Google Maps)

3.1 The B-23

The B-23 is one of the 8 important entrances to Barcelona. In fact it is one of the most demanded freeways towards Barcelona: in working days it has 14% of traffic demand (Generalitat de Catalunya). It links the city with Molins de Rei and it has current daily congestion during the morning (inbound direction) and evening (outbound direction) rush hours. In a normal weekday the morning rush hour can reach a travel time index higher than 3 (Janot, 2013). Travel time index compares the travel time between the studied scenario and the travel time in uncongested conditions. The highway can be divided in two parts: the outer part, which has 4 lanes per direction and its highest speed limit is 100km/h and the inner part, which consist of 3 lanes and has a speed limit of 80km/h (**Figure 6**). In the transition of the two parts (PK 7,28 to PK 6,15) the highway consist of 2 lanes. There are also some transition sections at both ends of the highway, where the speed limits vary from 120 to 50km/h.

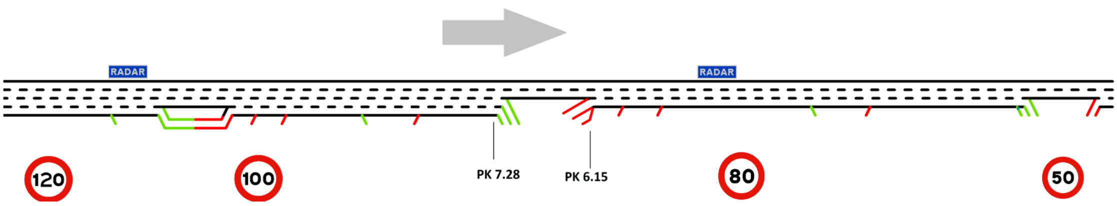

Figure 6 – Scheme of the B-23

The B-23 is equipped with VSS every 500m or 1000 m. It also has surveillance traffic detectors every 500m and TV cameras every 1 km. It is also provided with LPR (license plate recognition) at both ends. Nevertheless the TMC (traffic management center) has some technical limitations: only three cameras can record at the same time and only four detectors can simultaneously measure individual data. Thus the micro and the lane changing analyses are limited.

3.2 Data collection

The data is collected only Tuesdays, Wednesdays and Thursdays in order to avoid significant changes in demand across days. Since it is not a simulation, but real data measured on different days, it is impossible to ensure that the demand stays constant. To reduce the effects of different days, the experiment was aborted if there was bad weather or a traffic accident. The experiment is only carried out during three hours every day, in the morning peak: from 7am to 10am. Various scenarios were defined and recorded for seven days. Cameras were active either in the downstream part or the upstream part of the highway. In **Annex A.1** a scheme of the different scenarios can be found.

Three types of detectors are installed on the B-23. All types of detectors compute the data for each one of the 3 lanes. For all the detectors the data is aggregated in periods of 1 minute. The detectors work as follows:

- ETD(S): Simple loop detector. They can only record occupancy rates and vehicle count. Total vehicle count [vehicles] and the occupancy [%] are aggregated data for periods of 1 minute.
- ETD: Inductive double loop detector. They consist on two consecutive single loop detectors, and measures the time that the car needs to go from one detector to the other. This allows the calculation of vehicle time-mean speed [km/h]. They also can estimate the car length by knowing the occupancy and the speed. But in this thesis only the time-mean speed is relevant data.
- ETD(DT): Triple technology traffic detector. This kind of detectors are non-intrusive and were installed on highway sections where no vehicle speed data was available. They carry out measurements with three different technologies: ultrasound, Doppler radar and passive infrared detection. These methods do not over count vehicles.

3.3 Section to analyze

The experiment generated a huge database, which can be consulted at the *dropbox* site: https://www.dropbox.com/sh/es3kzo5hjb9rje3/inIzGEFE1 . For the purpose of this thesis, it is essential that the section to examine has a camera, to count the number of lane changes. It is also important that the speed limits are respected. Literature confirms that credibility of speed limits highly influence the speed limit compliance (Goldenbeld & Van Schagen, 2010) (Van Nes & et al., 2008). Credible speed limits are speed limits, which drivers consider to be reasonable due to the traffic and highway characteristics and weather conditions. Highly credible speed limits improve the drivers compliance of DSL. Additionally, as concluded in a precedent thesis done at the B-23 (Janot, 2013), the existence of a speed limit enforcement (radar) is essential for speed limit fulfillment. Otherwise the effects of speed limits are almost negligible in Spain.

In order to avoid mandatory lane changes, the farther from junctions, the better results will be obtained. It is also important that both congested and uncongested periods exist, as is intended to show a global understanding of how the number of lane changes maneuvers realized are related to different traffic conditions. Besides, it is crucial to ensure that capacity is reached. The only section that fulfills all these requirements is: PK 4,73. **Figure 7** (Soriguera & Sala, 2013) shows a scheme of the situation.

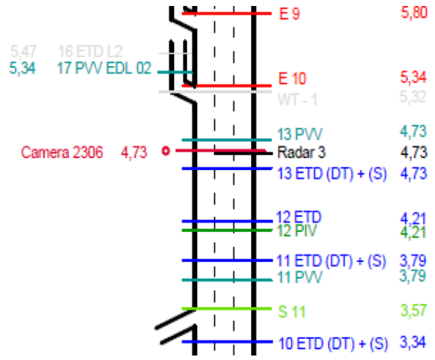

Figure 7 – Scheme of highway near PK 4,73

As this section is in the downstream part of the highway, the only data we can examine is from days 5 to 7. We also could valuate the day 1 data, but since the VSL was variable, the results could not be contrasted nor compared with the other days.

Table 1 Summarizes the conditions for each day in the section of study.

Table 1 – Summary of section characteristics

PK 4,73	Day 5	Day 6	Day 7
Speed Limit	80 km/h	60 km/h	40km/h
Camera	2306	2306	2306
Detector	ETD13 (DT) +(S)	ETD13 (DT) +(S)	ETD13 (DT) +(S)

(a)

(b)

Figure 8 – Situation of PK 4,73 in B-23 (Google Maps)
(a) Photograph of situation
(b) Map of situation

The section of study is not a bottleneck itself, all the congestions are due to spill back from sections downstream. Some errors were found in the data of ETD13, detailed information about them and their correction can be found in **Annex A.2**.

The decision to study section PK4,73 was taken because it is expected that DSL are accomplished, due to the existence of radar enforcement. It is important to make sure that this happens. A closer look to the sectional average speeds can be found in **Figure 9**. Sectional average speeds are represented for each day across time; the horizontal lines correspond to the DSL for each day.

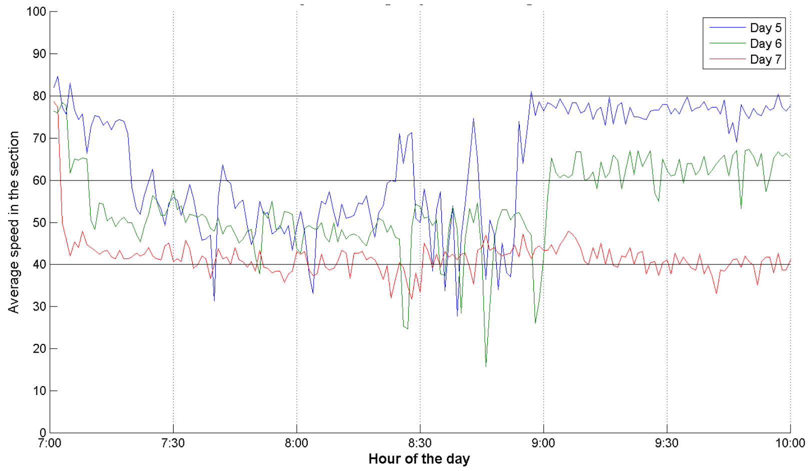

Figure 9 – Mean sectional speed across time

It is relevant to remind that speed limit compliance is highly related to the credibility of speed limits, as mentioned previously. This explains why the firsts minutes in day 6 and day 7, drivers are violating the DSL. It is also a good explanation of why DSL in day 5 are more accomplished than in the other days, **Figure 9.** It also shows that for the first minutes of day 6 and 7, the drivers ignore SL. From 9h to 10h in day 6 vehicles are often faster than the corresponding SL, they reach values of 67km/h and, as the average speed is not 10km/h above the speed limit, it is not considered speeding (Soriguera & Sala, 2013). The same criteria is used for day 7. To sum up, ignoring the firsts 5 minutes (day 6) and the first 3 minutes (day 7), will allow the data to be analyzed without concern. The enforced limits have a high enough compliance rate as show some contour plots (Soriguera & Sala, 2013), that can be found in the **Annex A.3**.

4.General analysis of the highway states and variables

4.1 Free-flowing and congested periods

All the recorded data through the three hours experiment for the three different days is shown in **Figure 10**. Each point in the graphic represents the aggregated data for one minute. Flow rates [vehicles/hour] are referred to the whole section. These flow-occupancy diagrams show one of the most important findings of this thesis. For a DSL of 80km/h high flows can be reached for a wide range of speeds, from 50 to 75km/h. This implies a strong flatness of the flow-occupancy diagram. Critical speed is between 50km/h and 55km/h, which is considerably lower than expected for a highway and critical occupancy is around 26%. Additionally, a clearly under-critical speed (40km/h) does not reduce the capacity of the highway as expected from previous studies. Day 6, with a slightly over-critical speed of 60km/h has also the same maximal flow rate, hence there is no capacity increase. Thus, different days serve the same flow, but day 6 and 7 at higher occupancies and lower speed than day 5, which will lead to longer travel times. The graphic also shows a significant shift of the critical occupancy to higher values for sub-critical speed limit.

Since there is no much data for congested states, the congested branch is not clearly discernible and it can only be assumed that it is the same, but with various occupancy starts.

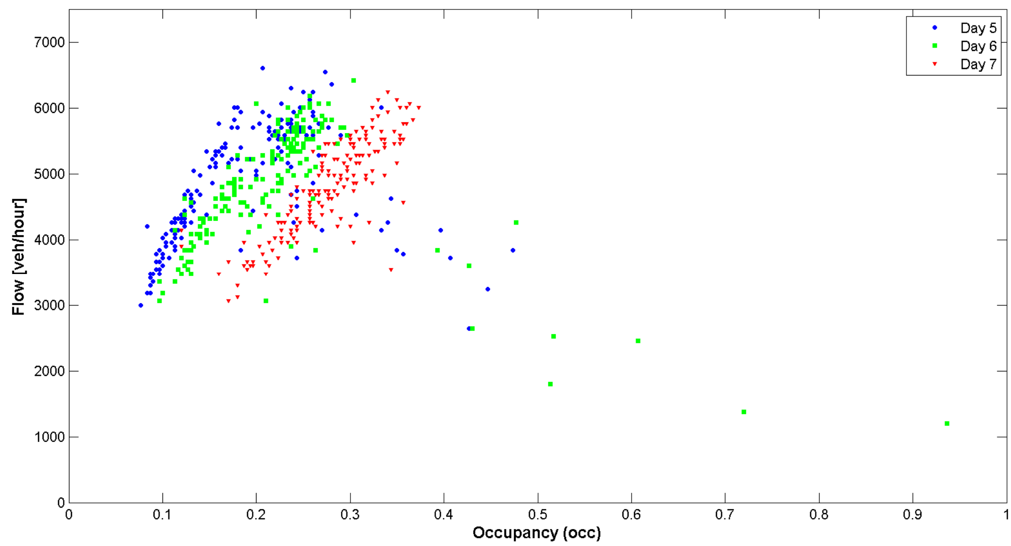

Figure 10 – Flow – occupancy diagram for minute aggregated data

Three hours of experiment are lots of data and it can be difficult to see any tendencies, due to the high dispersion. In order to be able to extract quantitative and robust values for these observations, it is needed to aggregate the data in bigger periods of time, such as stationary periods, which will allow a better understanding of the traffic behavior.

It is also important to distinguish between congested and free-flow periods. Congestion is characterized by high occupancies and low flow rates. For this reason we look at the oblique cumulative curves and search the time when there is a change of slope. The use of oblique cumulative curves is very useful. The concept of modified cumulative curves is to subtract a constant value multiplied by time (constant·t) to the initial cumulative curve. With this transformation, it is easier to see periods with constant flow/occupancy and periods where one or both of these variables increase or decrease. We can repeat this procedure for different constants (background values), since the background reduction does not alter the occurrence times of flow/occupancy changes on the cumulative curve. For higher background values, the changes of slopes are easier to detect.

q_0 : Background flow

b_0 : Background occupancy

c_0 : Background lane changes

Corresponding to day 6 of the experiment and section PK 4,73 congestion starts shortly before 8:30h and ends around 9h, c.f. **Figure 11**. There are also some perturbations at approximately 7:15 and 7:45h. A closer look to day 6 and day 5 cumulative curves can be found in **Annex B**. **Figure 11** also states that every time there is a change of state, lane changes are influenced and make sudden changes. This has not been contrasted, but is

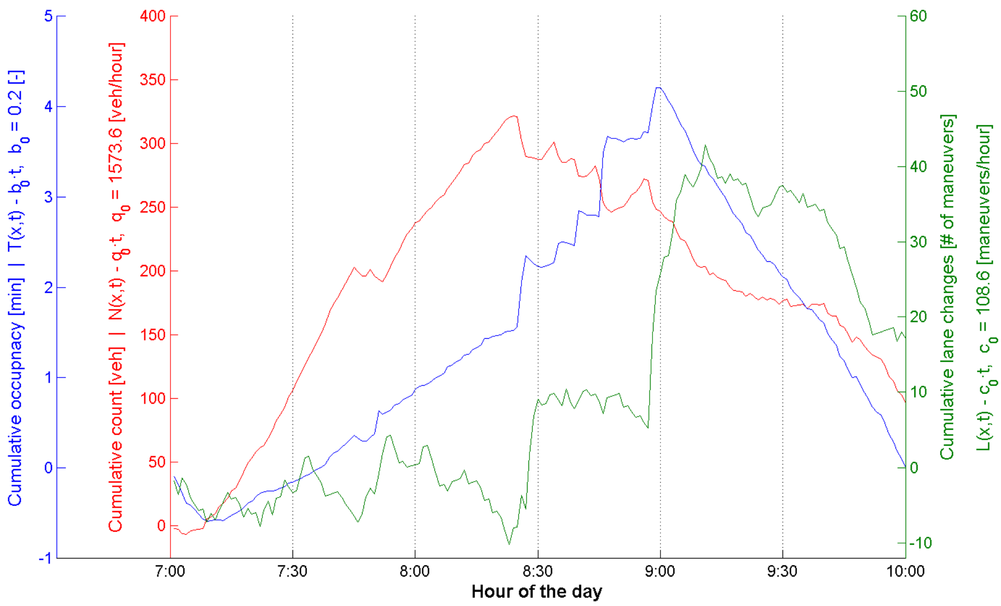

Figure 11 – Cumulative curves day 6

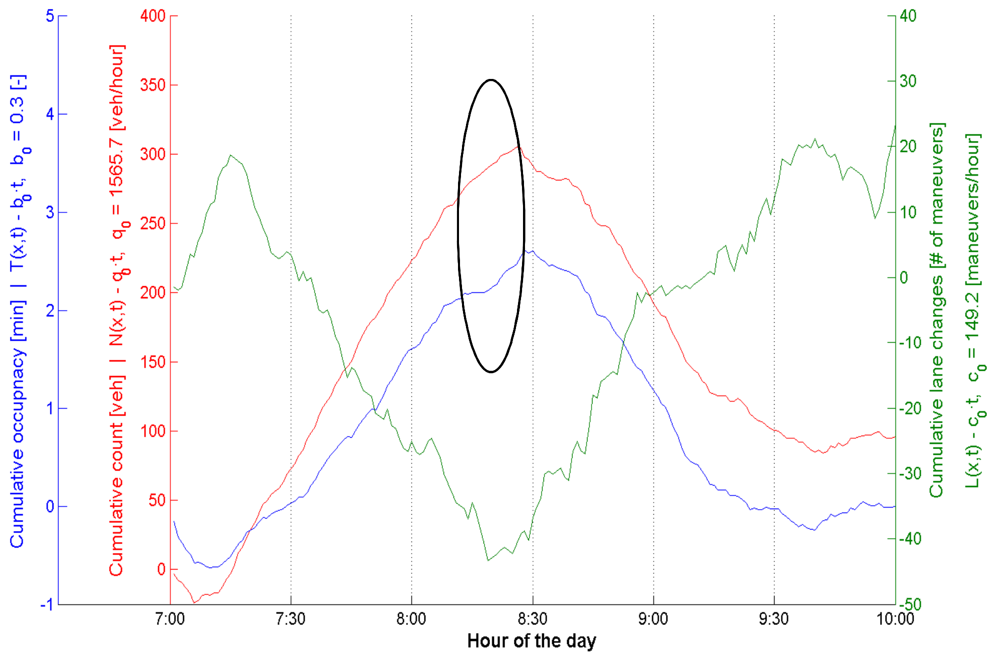

Figure 12 – Cumulative curves Day 7.

In day 7 cumulative occupancy and cumulative count follow the same trend, only around 8:20h there is an increase of occupancy where the cumulative count slope stays the same, **Figure 12**. This is the only congestion in that day. **Table 2** contains all the congested periods for each day.

Table 2 – Congested periods

Day 5	7:39-7:40	8:02-8:05	8:29-8:39	8:44-8:53
Day 6	7:46-7:53	8:24-8:30	8:31-8:47	8:57-9:00
Day 7	8:20-8:28			

4.2 Stationary periods

Stationary periods (SP) are defined as periods of time in which all parameters of traffic are constant or nearly constant. They can be characterized with an average flow rate and an average occupancy. Thereupon it is important to define the maximum acceptable deviations for minute values to the average values of the SP. The limits set are absolute differences.

$$|q_m - q_i| \leq 7\,\frac{veh}{min} \tag{1}$$

$$|occ_m - occ_i| \leq 5\% \tag{2}$$

In addition, since the aim of the definition of the stationary periods is to relate occupancies with lane changing rates, it is important that L(t) has also a nearly constant slope. The restriction used to check the lane changing stationareity is:

$$|lanech_m - lanech_i| \leq 3\ lane\ changes \tag{3}$$

The best way to choose the stationary periods is to identify periods with constant slope in the oblique cumulative curves. The bigger the background values are, the more abrupt are changes in slope. For this reason, and because the strict definition is already set with equations (1) to (3), it can be used a smaller background value, in order to be more tolerant with the definition of SP. Still, it is useful to examine the graphs used to define congested and uncongested periods (**Figure 11**). This way there are some preliminary SP defined **Figure 13**. In order to see better the slopes, the analyses are done for periods of one hour for each day. Exemplified is the 7-8h period and the 8-9h period of day 6 in **Figure 14** and **Figure 15**, respectively. The other plots can be found in **Annex C.1**.

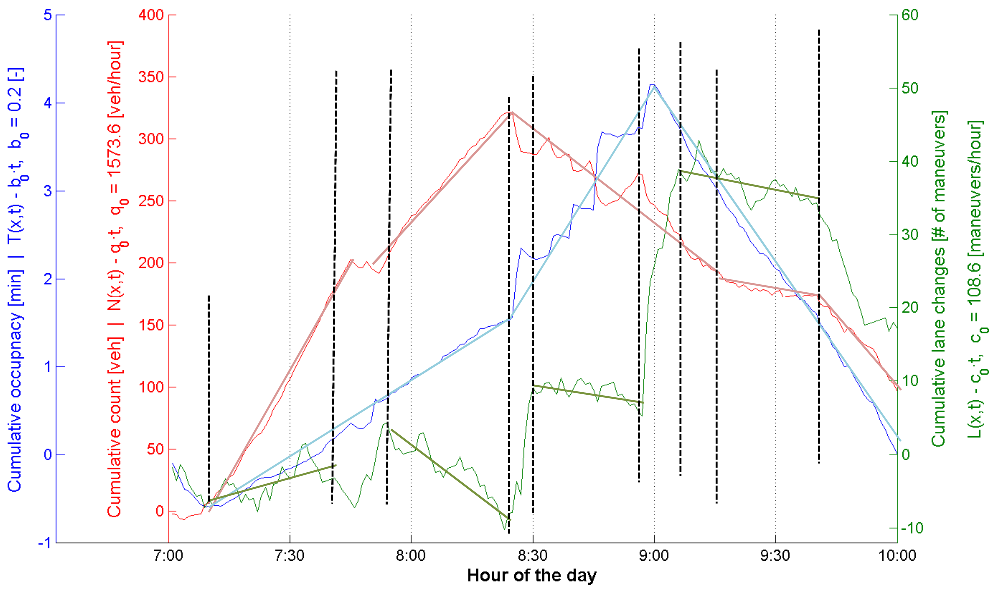

Figure 13 – Cumulative curves in day 6 with approximation of periods with constant slope

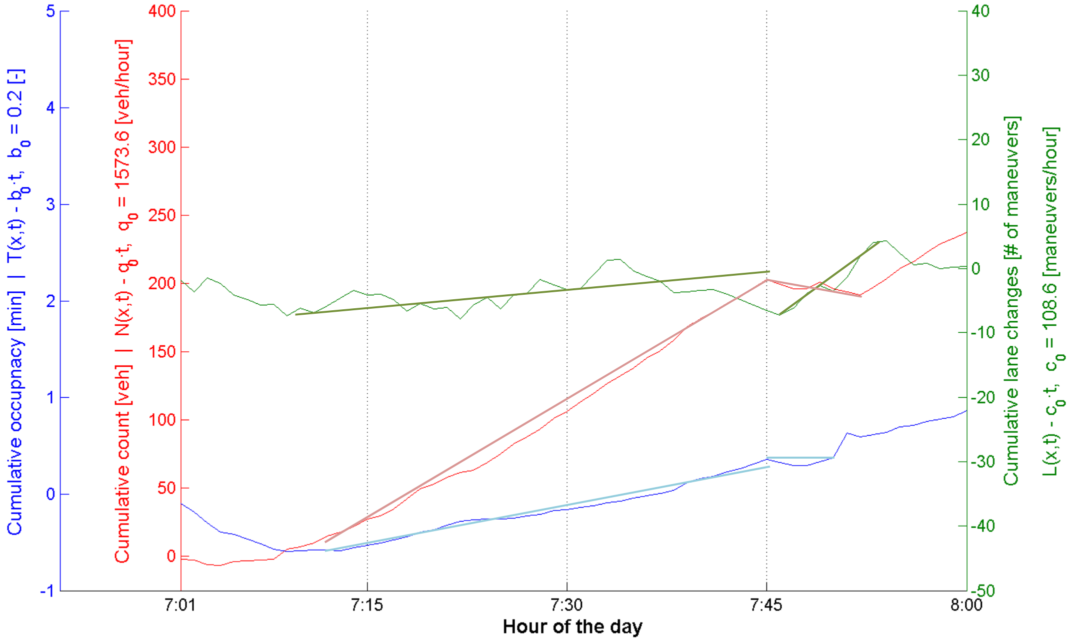

Figure 14 – Cumulative curves for day 6 from 7h to 8h

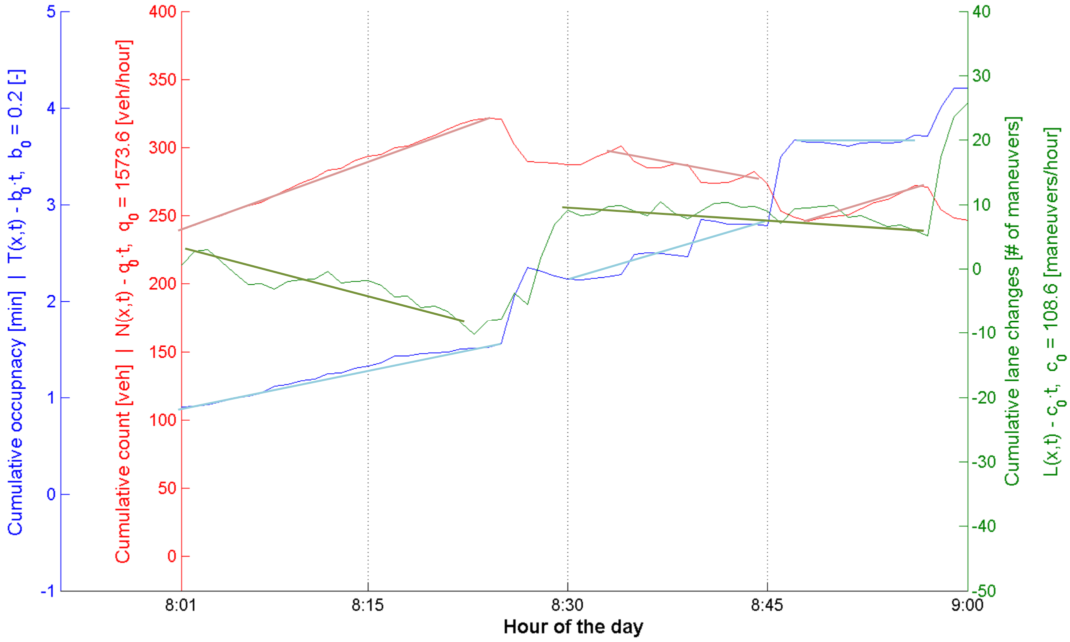

Figure 15 – Cumulative curves for day 6 from 8h to 9h

On the other hand, since the available data are measurements in a real situation, it is not perfect. There may be values that do not seem to correspond to a stationary period but following and precedent minutes clearly correspond to the same SP. Thus, I have accepted some values that diverge more than the boundaries set in equations (1), (2) and (3).

In addition, as exposed in **Figure 15**, in congested states, stationary periods are shorter and have higher deviations to the mean values. For this reason, other conditions for congested stationary periods were defined, which are more relaxed, and a duration as short as 2 or 3 minutes was accepted. This is important, because if same conditions (1), (2) and (3) would have been applied, we would have ended up with no representative values of congested states. The restrictions for congested states are the followings:

$$|q_m - q_i| \leq 15 \frac{veh}{min} \tag{4}$$

$$|occ_m - occ_i| \leq 10\% \quad (5)$$

$$|lanech_m - lanech_i| \leq 5 \; lane\ changes \quad (6)$$

Table 3 summarizes the characteristics of all the defined stationary periods. It shows how many minutes (over 180 minutes) are considered to pertain to stationary periods. Furthermore, there is indicated how many minutes were outside of the ranges defined in (1), (2), (3), (4), (5) and (6). Which represent 7,27% of all the minutes pertaining to stationary periods on day 5; 10,17% on day 6 and 2,68% over the total minutes of day 7.

Table 3 – Summary of stationary periods:

SUMMARY OF SP	#min SP cong	#min SP uncong	% SP	Number of SP	average duration SP	maximal duration SP	minimal duration SP	#min out of rang uncong	#min out of rang cong	#min out of rang total
Day 5	27	138	91.67	15	11:00	34	2	6	6	12
Day 6	36	141	98.33	15	12:20	23	4	6	12	18
Day 7	22	127	82.78	16	9:31	25	4	0	4	4

In **Annex C.2** are located other tables, one for each day, which have more detailed information for each stationary period. And there is also a list of all the congested stationary periods.

After defining the stationary periods it is interesting to watch at how the data looks like. It is important that we have stationary periods defined in uncongested states, but also that we have some stationary periods that represent the congested states. The FD for stationary periods is showed in **Figure 16** for all days together.

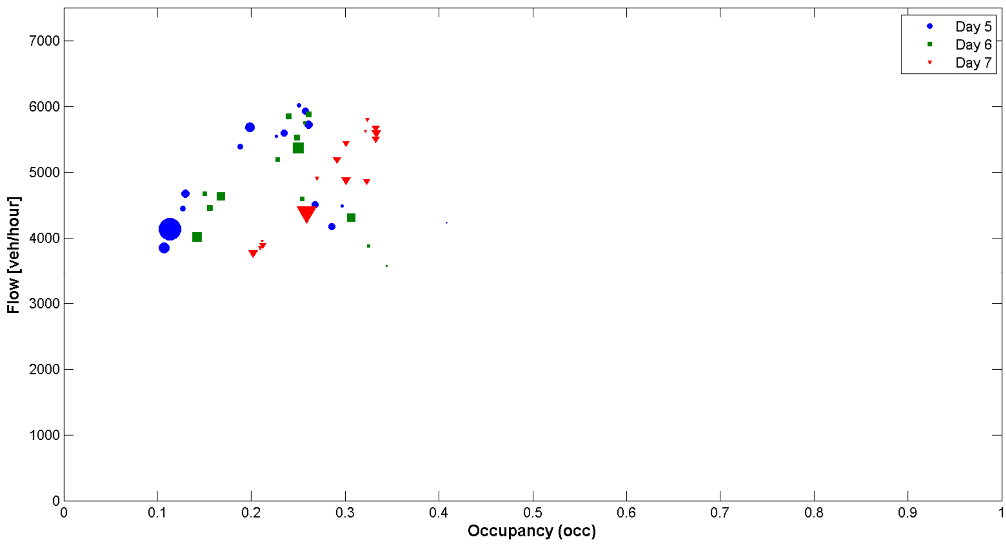

Figure 16 – Sectional flow vs average occupancy, for each stationary period

With over-critical speed limits, the free-flow branch has two parts: for low occupancies, the slope is constant and proportional to the DSL, but for higher occupancies there is a reduction of speed until critical speed is reached. Thus, we can assume that the uncongested branch has two groups of stationary periods (**Figures 17 and 18**), depending on the speed. This tendency could also be seen in **Figure 10**, where free-flow part of the FD seems to have two different branches, more clearly around an occupancy rate of 20%. This phenomenon has no known explanation and it is the first time that has been observed.

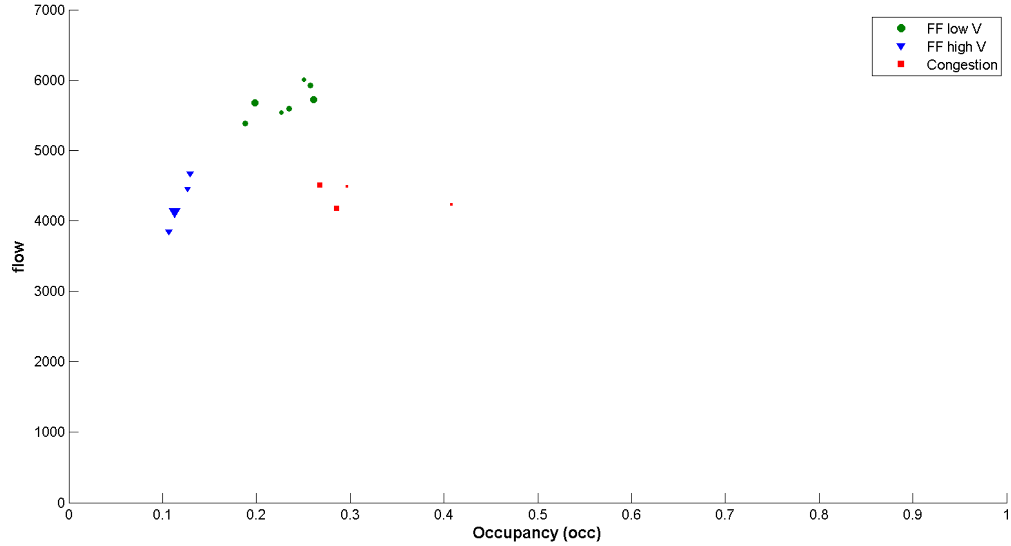

Figure 17 – Sectional flow vs average occupancy, for each stationary period. Day 5.

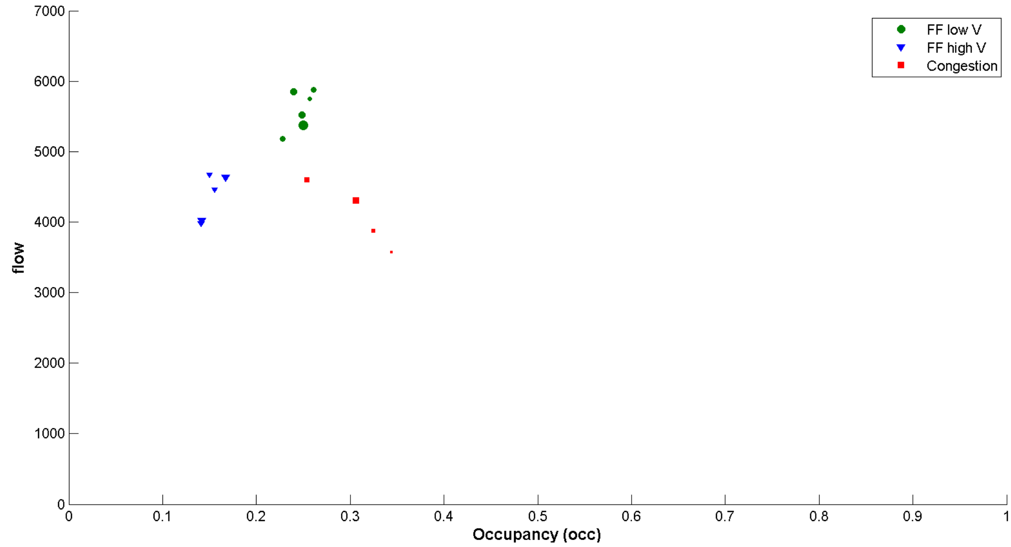

Figure 18 – Sectional flow vs average occupancy, for each stationary period. Day 6.

Capacity is actually reached at a significantly lower free-flow speed than the one observed for low occupancies. **Table 4** supports this statement by indicating the average speeds of the different groups of free flow periods. This surprising behavior is contrasted by a t-student test in **Annex C.3**. Additionally to this contrast of hypothesis, in the same Annex some tables synopsize the characteristics of the uncongested stationary periods.

Table 4 – Average speeds for the two groups of uncongested SP:

Day	Free Flow Speed at low occupacies	Free Flow Speed arround capacity
Day 5	76,85 km/h	55,70 km/h
Day 6	64,32 km/h	50,35 km/h

On the other hand, in day 7 this “double-branch” in free-flow states is not observed. The free-flow branch has approximately a constant slope for all under-critical occupancies, **Figure 21**. The free-flow average speed for day 7 is 41,9km/h. Further research may help to reach a deeper understanding of this peculiarity.

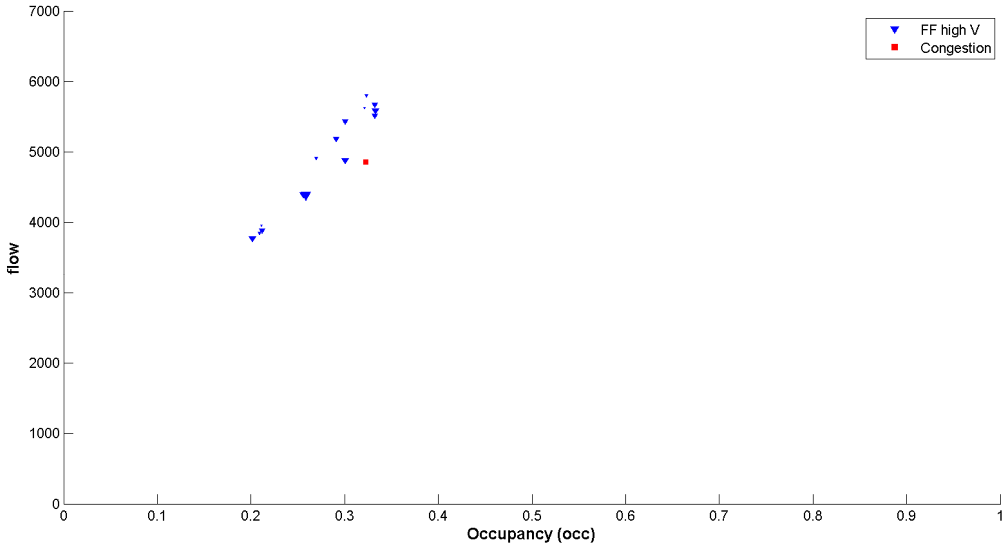

Figure 19 – Sectional flow vs average occupancy, for each stationary period. Day 7.

5 Effects of per lane homogeneity

The aim of this section is to compare the differences on flow, occupancy rates or speed across lanes, and analyze how these differences are affected by different speed limits. To be consistent with the whole investigation, the graphs presented in this chapter relate the lane characteristics to the overall sectional occupancy. There are two approaches to evaluate the differences between lanes. One is to compare the absolute lane characteristics, and the other one is to compare the rate of the lane values over the sectional values. This second option allows having a quick understanding how lanes are used.

$$\frac{q_i}{q_{section}/_3} \qquad \frac{v_i}{v_{section}} \qquad \frac{occ_i}{occ_{section}}$$

For these "i" indicates the lane. The lanes have been labeled with number from 1 to 3, **Figure 20**.

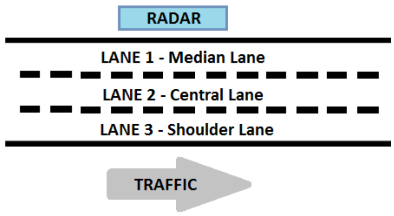

Figure 20 – Numeration of Lanes

Reproducing the flow for each lane is useful to see if one lane is underused. This also can be observed with the occupancy repartition. For all the three variables, the values obtained from the ratio, can be interpreted as:

- <1 : lane i has lower flow, occupancy or speed than the average of the section
- >1 : lane i has higher flow, occupancy or speed than the sectional average
- =1 : lane i has the same flow, occupancy or speed as the average of the section

Representing all minutes generates a sparse graph in which it is difficult to see clear tendencies. For this reason the graphs presented in this chapter are grouped data of minutes corresponding to similar occupancies, in occupancy bins. The distribution of the minutes across sectional occupancy for each day can be found in **Table 5**.

Table 5 – Number of minutes pertaining to each occupancy bin:

Sectional occupancy			Day 5	Day 6	Day 7
0.075	to	0.125	55	12	2
0.125	to	0.175	31	41	3
0.175	to	0.225	31	43	23
0.225	to	0.275	48	68	54
0.275	to	0.325	4	7	66
0.325	to	0.375	6		32
0.375	to	0.425	2	1	
0.425	to	0.475	3	2	
0.475	to	0.525		3	
0.525	to	0.575			
0.575	to	0.625		1	
0.625	to	0.675			
0.675	to	0.725		1	
0.725	to	0.775			
0.775	to	0.825			
0.825	to	0.875			
0.875	to	0.925			
0.925	to	0.975		1	

5.1 Differences in occupancies

Day 5 and 6 have a similar behavior regarding lane occupancies. In uncongested situations the median lane (Lane 1) is underused. While approaching the critical occupancy, the difference in occupancy between the lanes decreases and, around capacity, all lanes are equally dense. In day 5 and 6 around capacity the road is clearly homogeneous.

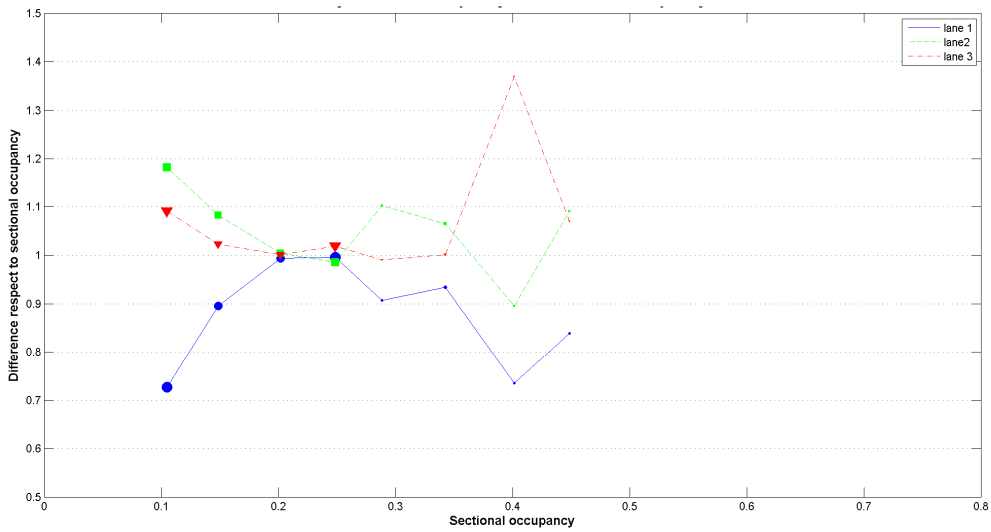

Figure 21 – Lane occupancy over sectional occupancy. Day 5.

After reaching capacity, in day 5 the Lane 1 seems to become once again underused. Differences between lane occupancies grow with high sectional occupancies (occ > 30%). This behavior is not clear for day 6, although the differences also increase for high occupancies, at 30% the differences are still small. For this range of occupancy 25% to 30% there is a harmonization of occupancies due to SL of 60km/h. But there is no homogenization effect for low occupancies: For day 5, the highest divergence from the average occupancy has a maximum value of +18,2% for lane 2 and -27,3% for lane 1. While in day 6, these values are even higher: +27,1% for lane 2 and -38,6% for lane 1.

The thickness of the represented points correspond to the amount of minutes belonging to a same occupancy bin. For this reason the function for higher occupancies than 0.25 is not representative nor unequivocal. A conclusion is that in congested periods there is no homogeneity in lanes occupancy.

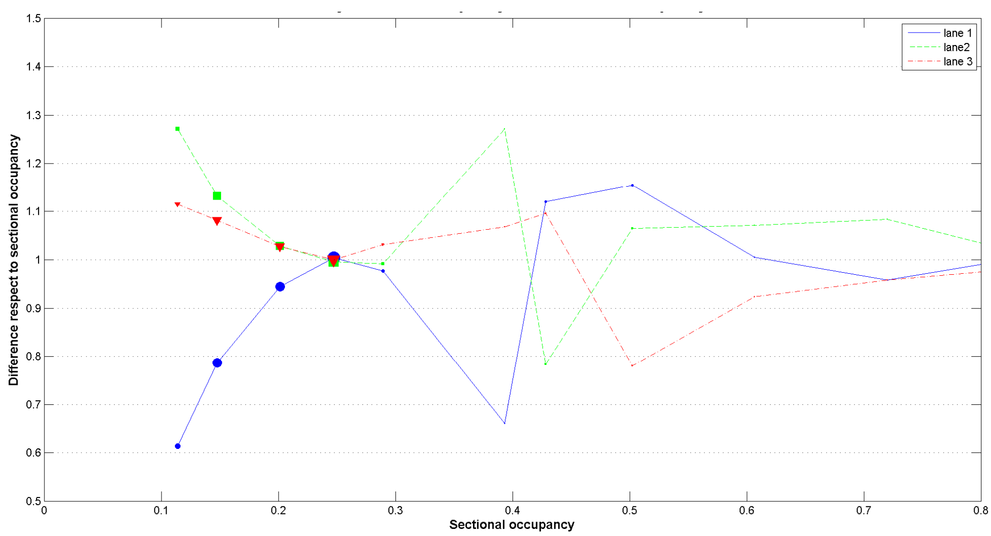

Figure 22 – Lane occupancy over sectional occupancy. Day 6

On the other hand, the pattern in day 7 is clearly not similar to the other days. There is not such a big difference between lane occupancies at low sectional occupancy. In addition, sectional occupancies from 30% to 40% are still similar trough lanes. In day 7, the maximum deviations from sectional occupancy are +11,3% for lane2 and -12% for the median.

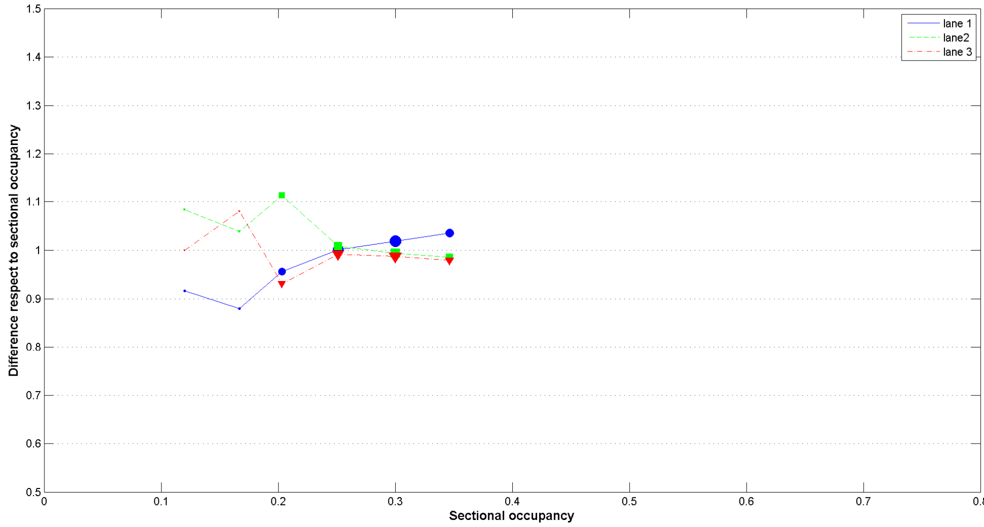

Figure 23 – Lane occupancy over sectional occupancy. Day 7

To sum up, there is an intrinsic homogenization of occupancy across lanes near capacity, but it is not related to DSL. Further can be said, that clearly sub-critical SL have a generalized harmonization effect.

5.2 Differences in flows

Flow does also have a cross phenomenon, which had also been reported (Knoop, 2010). As arise with lane occupancy, flow in lane 1 is way lower than the average flow per lane. A maximal deviation of -20,3% for day 5, a -30,4% for day 6 but only a -8,5% for day 7. Again, a homogenization can be distinguished for clearly under-critical SL, but not for SL of 60km/h. For overcritical occupancies, flow in lane 1 stays the highest for day 5 and 7: **Figure 24 and 26**. Except for the few minutes of really low occupancy (10%) in day 7, it shows the same pattern than day 5. These very low sectional occupancy rates correspond to the first 2 minutes of the experiment, time when the SL is not respected by the drivers (c.f. chapter 3.4). Again, the overcritical representation of the graph in day 6 is not representative.

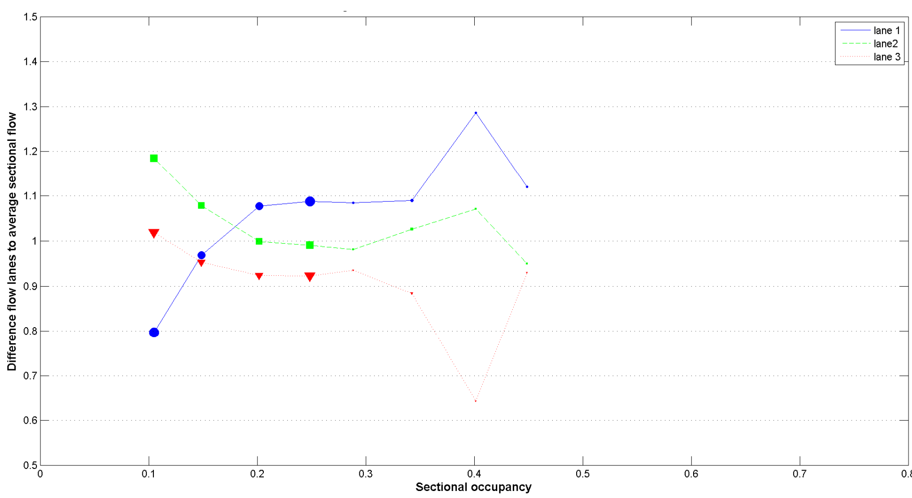

Figure 24 – Flow rates over sectional occupancy. Day 5.

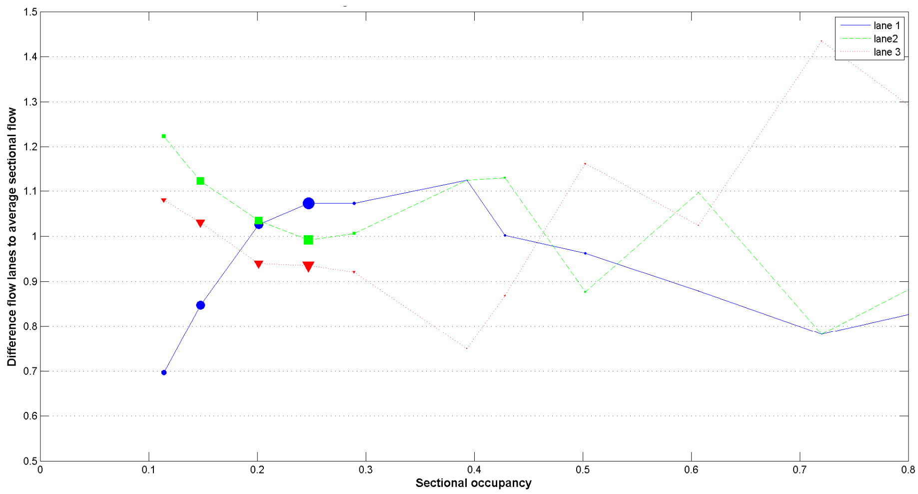

Figure 25 – Flow rates over sectional occupancy. Day 6.

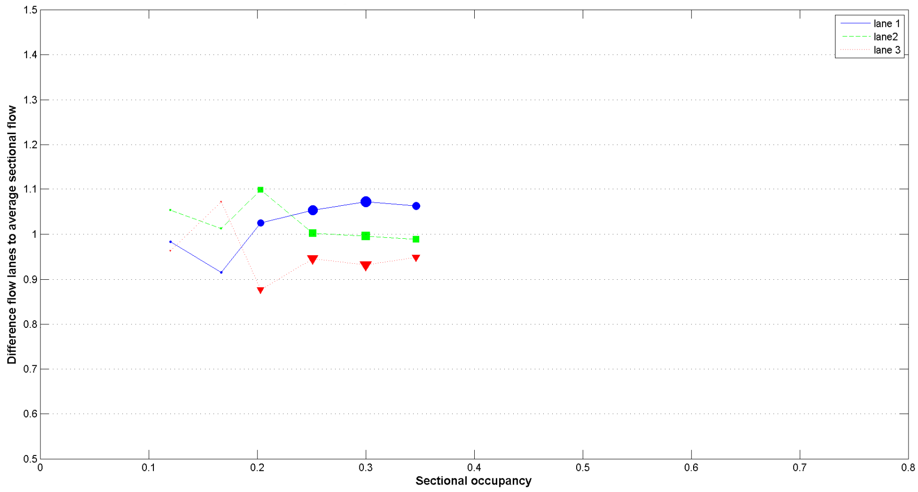

Figure 26 – Flow rates over sectional occupancy. Day 7.

Another way to compare the flow in different lanes is to compute the percentage of flow that every lane carries. This can be seen in the graphs from **Annex D**. In day 7 the maximum flow difference between lanes is a 7,4% of the total flow, which corresponds to 4,52veh/min. For all days, the repartition of flow corresponds approximately to 36% - 33% - 31% around capacity. This distribution of flow stays more or less stable for higher occupancies until an occupancy rate from approximately 35%.

5.3 Differences in speeds

In Spain, the shoulder lane is the lane where everyone should drive, and the other two lanes should only be used to overtake other cars. This is not always respected, but the distribution of speeds is accomplished. The fastest drivers travel through lane 1 and the slowest travel on lane 3. This is clear for uncongested states, because if there are very few vehicles in the road, they are able to distribute themselves and travel at different speeds in different lanes. Although in this section this is clearly not the case. Lane 1 is the fastest one, but lane 2 is the slowest, **Figures 27 to 29**. Some hypothesis about this rare behavior are the following:

- Lane 3 is faster than the lane 2, because the radar measures only lanes 1 and 2.
- Lane 2 is the slowest, as the absolute number of lane changes is higher in this lane: it receives cars from the other two lanes.

Neither of these hypothesis could be contrasted, but the first one has certainly an influence on the speeds.

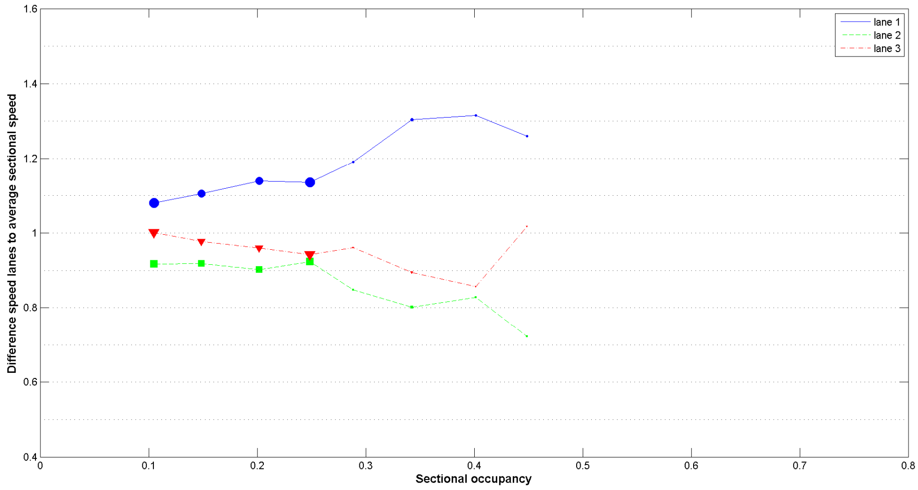

Figure 27 – Lane Speed over average speed across sectional occupancy. Day 5

The relative differences in speed to the average section values are stable (or experience a slightly increment) for uncongested periods, but increase substantially for congested states. **Figures 27 to 29**. During congestion, the speed is in general much lower and only small increases of speed differences lead to significantly higher percentage difference. This can be stated comparing **Table 6** with **Figure 28**, where the speed differences to the sectional speed average are presented for day 6.

Table 6 – Lane speed differences to the secction, absolute values, day6.

Sectional occupancy	L1	L2	L3	*Section*
0.075 to 0.125	7.51	-7.48	-0.04	*68.14*
0.125 to 0.175	7.16	-7.08	-0.08	*64.06*
0.175 to 0.225	7.18	-5.22	-1.96	*53.79*
0.225 to 0.275	5.74	-4.02	-1.72	*49.58*
0.275 to 0.325	6.39	-4.09	-2.30	*46.38*
0.325 to 0.375				
0.375 to 0.425	3.33	-4.67	1.33	*29.67*
0.425 to 0.475	6.39	-5.72	-0.67	*34.50*
0.475 to 0.525	8.84	-10.12	1.29	*29.44*
0.525 to 0.575				
0.575 to 0.625	6.67	-11.33	4.67	*28.33*
0.625 to 0.675				
0.675 to 0.725	11.67	-5.33	-6.33	*25.33*
0.725 to 0.775				
0.775 to 0.825				
0.825 to 0.875				
0.875 to 0.925				
0.925 to 0.975	1.33	-4.67	3.33	*15.67*

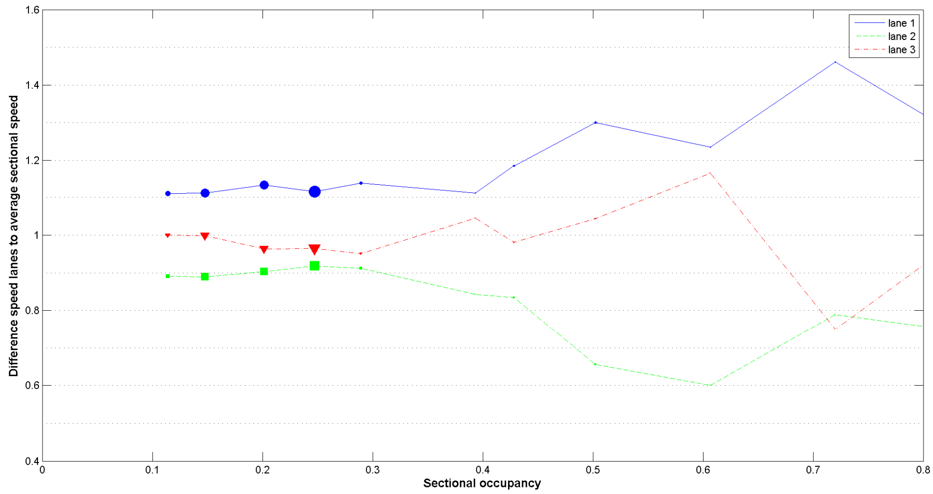

Figure 28 – Lane Speed over average speed across sectional occupancy. Day 6

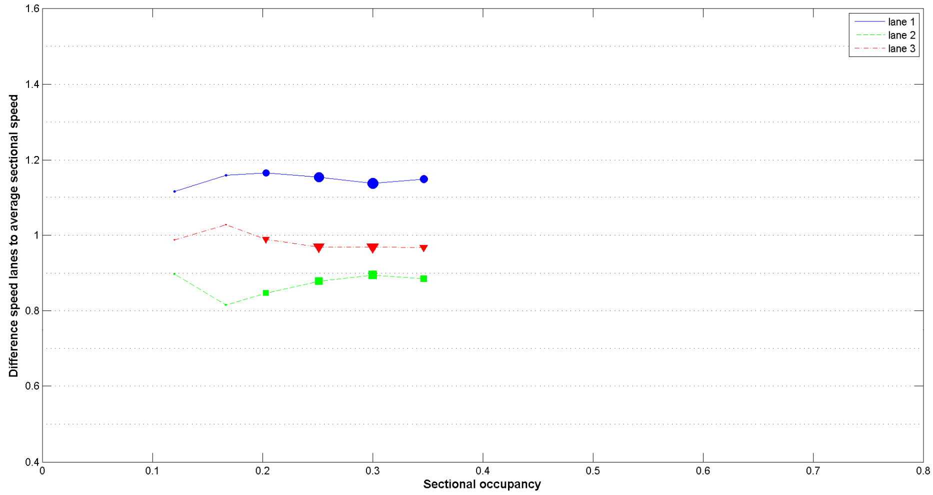

Figure 29 – Lane Speed over average speed across sectional occupancy. Day 7

In uncongested conditions, lower DSL cause slightly higher percentage differences in speeds. In chapter 1.2 was mentioned that DSL may reduce de variance of the average speeds between lanes, but this results seem to disconfirm what was assessed in previous investigations. With the evaluation from the available data, it cannot be stated that DSL reduce speed differences respect no-DSL, as there is no data for no-DSL states.

6. Lane changing rates analysis

The main purpose of this chapter is to try to explain the lane changing activity. They are two different approaches to examine lane changes. The first one is to compare the different traffic states of the highway and see when do more lane changes maneuvers take place. For this purpose a sectional analysis is enough. The second approach is to relate the lane changes with the different occupancies or speeds between lanes. In other words, to see how highway homogeneity affects the number of lane changes. Further I will try to explain how the different speed limits affect this relationship.

6.1 Across whole section

It was thought that with lower occupancies less drivers will execute lane changes, because they can drive at the speed they want. One way to test this is to represent the lane changes rate for each SP as function of the average occupancy of the section. In order to understand better the behavior of the drivers, only uncongested stationary periods (defined in section 4.2) will be taken into account. The average values of these SP are represented in **Figure 30.** In the interest of keeping the relation between sectional occupancy and lane changing rate as simple as possible, a linear dependence between lane changing rates and occupancy was considered. Linear regressions for each day are computed, **Figure 30**. Regarding the graph, there is a SP for day 6 that is not considered for the linear regression (its shape is also different). We can "ignore" this SP, as it is not influenced by the section conditions but by a bottleneck downstream: drivers see that lane 2 is stopped which causes a lot of lane changing maneuvers in order to avoid this lane.

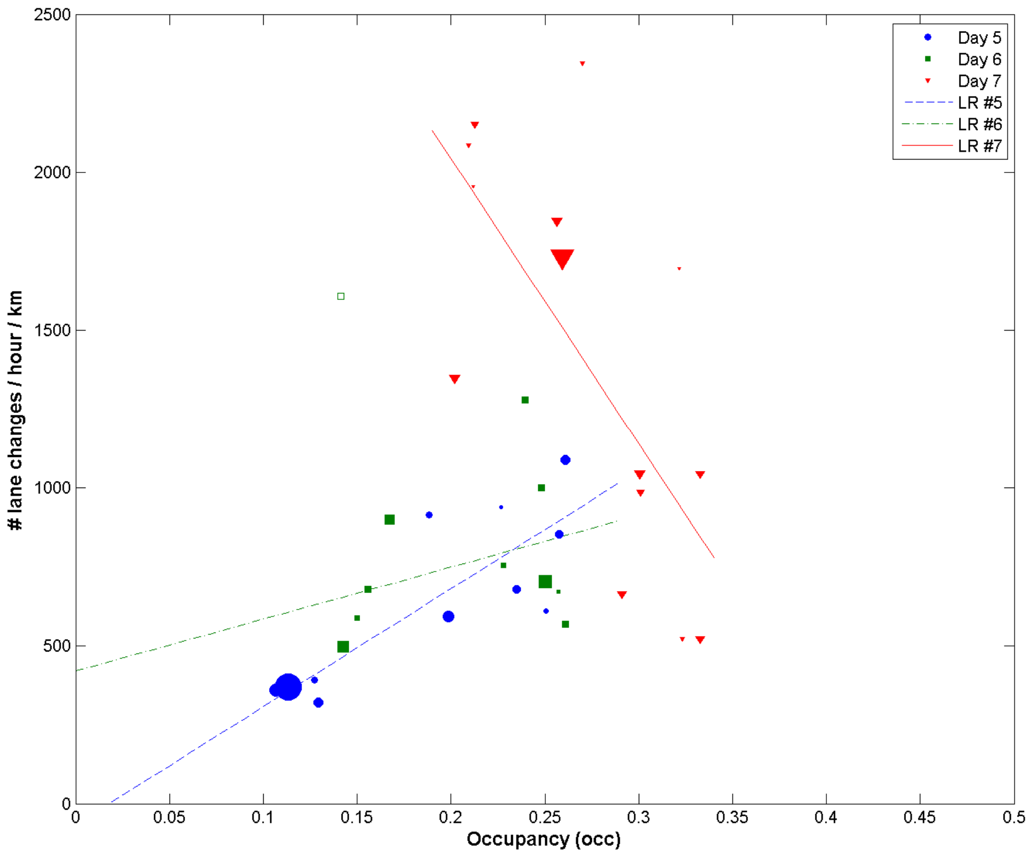

Figure 30 – Lane changing rate vs average occupancy (occ) for uncongested stationary periods

These results do not show what was expected: traffic society assumed that lower speed limits would reduce the number of lane changes. Day 5 and day 6 have a similar behavior, but day 6 has a higher lane changing rate than day 5 for low occupancies. In addition, under-critical DSL (day 7) causes even more lane changes at low occupancies. Thus, lane changing activity cannot be explained only with sectional occupancy rates.

On the other hand, around capacity the DSL seems to reduce lane changes for decreasing speed limit. To counterbalance that assertion, **Table 7** summarizes the traffic characteristics for the minutes with highest flow for each day.

Table 7 – SP with highest flow aggregated for each day:

Highest flow for uncongested SP	Avg. Flow [veh/h]	Avg. Occ. [-]	Avg. Speed [km/h]	Duration [min]	Avg. Lane change [lch/h/km]
Day 5	5954	0.26	53.33	17	767
Day 6	5880	0.26	49.67	11	569
Day 7	5720	0.33	41.33	18	521

The data summarized in **Table 7** is composed from one stationary period for days 5 and 6 and from two stationary periods for day 7.

As aforementioned, in section 4.2, free-flow states do not have a constant sectional speed. In fact, speed could be “split in two groups”. This fact suggests that lane change activity could also have a different behavior for these “groups”: one behavior for states with high speeds (similar to the speed limit) and a different one for uncongested states near capacity. For this reason, another analysis should be carried out, evaluating separately minutes with different speeds. With aggregate data is not possible to do this examination. Thus a micro analysis of the data is needed, which exceeds the possibilities of this Bachelor Thesis. Further research on this approach is recommended, as may lead to interesting findings.

In previous chapters, it was mentioned that it is important to understand the lane changing activity, not only in uncongested situations, but also in congested states. As a matter of fact, the collected data does not allow us to draw conclusions for congested states, since there are few and short congested stationary periods. This was clear from the beginning (**Figure 10**), since the congested branch is not clearly defined due to insufficient measurements at high occupancies.

Table 8 – Summary of congested stationary periods:

SUMMARY OF SPC	Flow [veh/h]	Occupancy [-]	Duration [min]	Lane cahnging rates [lane changes/h/km]
Day 5	4360	0.29	27	1468.60
Day 6	4260	0.30	36	1666.67
Day 7	5288	0.33	22	1185.77

Table 8 presents an aggregation of all the minutes belonging to stationary congested periods. This table does not show a tendency for the different DSL, but it manifests that in congestion, the lowest the flow rate is, the higher the number of lane changes is. It also expounds that lane changing rates are extremely higher than in free-flow conditions.

6.2 For each lane

As it has been found in the last chapter, lane changing activity cannot be completely explained by sectional occupancy. For this reason, this section introduces a quick overview of speed differences between adjoining lanes, to see if the lane changes may are better explained with this second approach. Since drivers typically think "*if the other lane goes faster, I will arrive earlier if I change lane*", this approach probably helps to have a better understanding of lane changes.

In the following figures, speed difference between lanes is represented as:

$$\textit{speed difference} = \frac{(v_1 - v_2)}{\min(v_1, v_2)}$$

$$\textit{speed difference} = \frac{(v_2 - v_3)}{\min(v_2, v_3)}$$

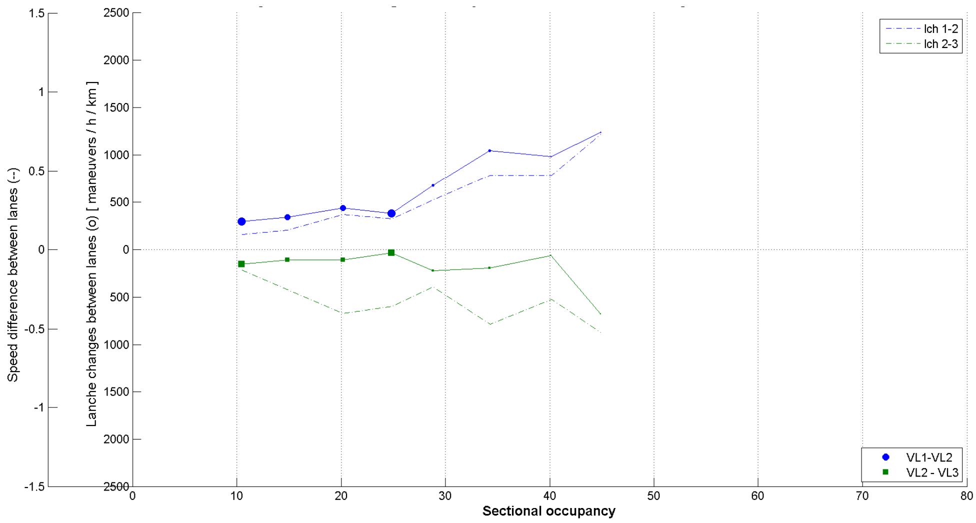

Figure 31 – Lane changing rate(LCR) and speed difference between lanes vs occ. Day 5

The first and clear evidence is that the speed differences between lane 2 and lane 3 are less significant than the speed differences between the median and center lane. Secondly, for the relation between these two last lanes the number lane changes maneuvers clearly follows the same pattern than the relative differences on speed.

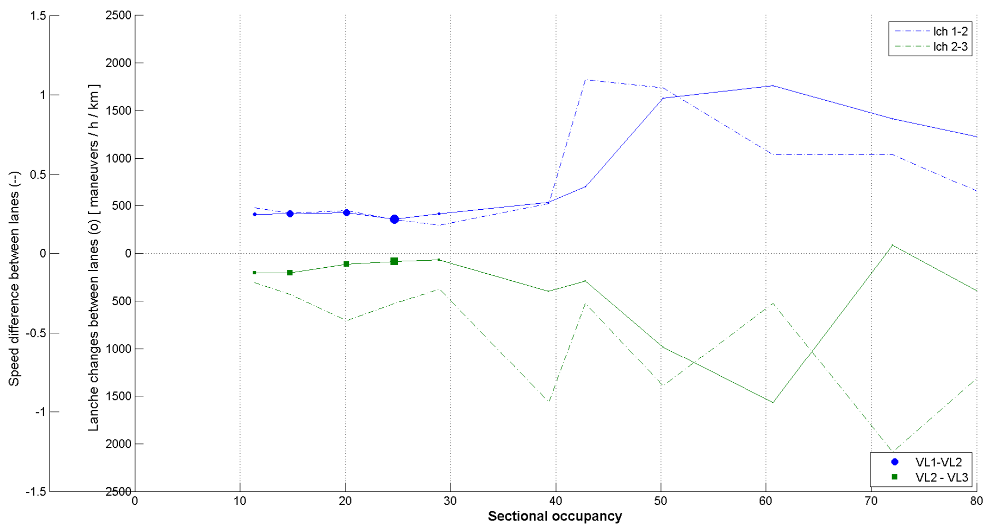

Figure 32 – LCR and speed difference between lanes vs occ. Day 6

This similarity for the lane change activity between lane 1 and lane 2 can be also recognized in days 6 and 7, **Figure 32** and **Figure 33**, respectively. Despite the clearness of this statement, this relation between speed variances and lane changing rates is not clear for lanes 2 and 3. Further research is needed or another approach should be considered, in order to have a better knowledge of lane changing activity.

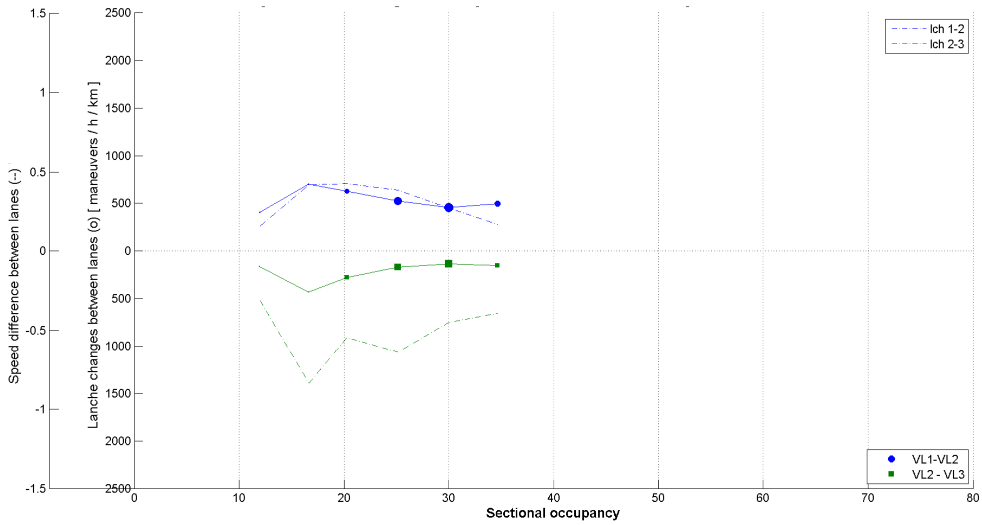

Figure 33 – LCR and speed difference between lanes vs occ. Day 7

7. Summary and conclusions

The studied section is located in the B-23 and data is collected for three different with different speed limits. Due to the flatness of the fundamental diagram the critical speed cannot be assessed perfectly but lies between 50km/h and 55km/h. Thus, we have two days with over-critical speed limit (80km/h and 60km/h) and one day with under-critical speed limit (40km/h). The main findings and conclusion of this thesis are the following:

Critical speed is substantially lower than highway standards. The fact that most of the drivers are either experienced or commuters and that this highway section has had a compliance enforcement for years may be an explanation for this behavior.

Over-critical speed limits have a reduced influence on traffic. There is a slight shifting of the critical occupancy to higher values for decreasing speed limits. The fundamental diagram for days 5 and 6 only differs on the slope at low occupancy rates, but presents no capacity increase. On the other hand, under-critical speed limit on day 7 shows a significant shifting of the critical occupancy, but there is no capacity decrease. This demonstrates that drivers are able to drive at very low speeds and very high occupancies, which prevents the traffic breakdown. This rejects the possibility that DSL can be used as mainline metering to complement ramp metering which has been proposed in previous investigations (Carlson, Papamichail, Papageorgiou, & Messmer, 2010) & (Hegyi, De Schutter, & Hellendoorn, 2005).

Further analysis of this thesis show that the inter-lane traffic homogenization effect of DSL is not pronounced. A clearly subcritical speed limit has a generalized harmonization effect for flows and occupancies: it reduces the inter-lane variance of occupancy and flow for uncongested states.

Regarding the occupancy variations between lanes it can be stated, that there is an intrinsic harmonization of occupancy across lanes near capacity. This behavior is independent of the DSL. For very low occupancies lane 1 is underused. At higher occupancies, the distribution of vehicles across lanes varies due to increasing lane changing activity and around capacity all lanes are equally dense. Over-critical speed limits clearly show these pattern, but day 6 slightly shifted to higher occupancies.

Further, lane flow rates show an analogous pattern to the lane occupancy rates. But the lane flow never reaches exactly a third of the total flow for all lanes. We have considered a flow distribution of 31%, 33% and 36% for lane 3, lane 2 and lane 1, respectively, as „homogenized“. Additionally, it is proved that decreasing the DSL causes a rise in inter-lane speed variations.

The number of lane changes maneuvers is much higher in congestion than in free-flow conditions. In uncongested states there are two different tendencies. For over-critical speed limits higher occupancy is linearly related to higher lane changing rates, while for under-critical speed limits more lane changes take place when occupancy rates are lower.

Thus, lowering the DSL will cause an increase in lane changing rates for low occupancies but a slight decrease of lane changes at critical occupancies for free-flow conditions. Lane changes are probably not only influenced by occupancy rates but also by differences between lanes, such as speed variances. Further research is required for this approach in order to reach a better understanding of lane changing activity. Differences in speed between the fastest and its adjacent lane are related to lane changes between these two lanes as both variables follow the same trend across sectional occupancy.

Annexes

ANNEX A : Detailed information about data collection and errors

A.1 Scenarios of the experiment

The following scenarios were created and recorded for the morning peak hour in the B-23:

Day#1 – 04.06.13

- Algorithm of SCT (Servei Català de Trànsit), the traffic administration, was used
- Data was recorded in the downstream part

Day#2 – 19.06.13

- Maximum speed limit for the outer part (100km/h) and for the inner part (80km/h)
- Data was recorded on the upstream part

Day#3 – 11.06.13

- Medium speed limit of 80km/h in the outer part and maximum for the inner part
- Data was recorded on the upstream part

Day#4 – 12.06.13

- Minimum speed limit (50km/h) in the outer part and maximum for the inner part
- Data was recorded on the upstream part

Day#5 – 06.06.13

- Maximum speed limit for the outer part and for the inner part
- Data was recorded on the downstream part

Day#6 – 13.06.13

- Medium speed limit of 60km/h in the inner part
- Data was recorded on the downstream part

Day#7 – 18.06.13

- Minimum speed limit (40km/h) in the inner part and medium for the outer part
- Data was recorded on the downstream part

A.2 Errors in the data

In the selected section we have two types of data. Data obtained from single loop detector (13S) and data obtained from triple technology traffic detector (13DT). In general, DT measurements of occupancy and number of vehicles are much more sensible to errors than S detectors. The source of this is the hypersensitivity of the occupancy measurements of the DT to the variations of the equipment alignment over the pavement (Soriguera & Sala, 2013). Thus, the data that will be analyzed is from simple loop detector.

Unfortunately, for some days one minute of data was lost in the simple loop detector, for all three lanes. This lack of data is probably caused by an error in the communication between devices.

Considering that there is only one minute lost, the reshuffle of data will not have a big influence in the results. For this reason, my decision was to replace the empty minutes with the measurements taken from DT detector. This minutes lost where:

Table 9 – Minutes where data was lost at ETD13(S)

Day 5	Day 7
9:58	8:43

It is important to mention that the values of DT are significantly lower than the values of the preceding and following minutes. This may be caused by the types of errors that the detectors suffer. In the measurements of loop detectors the maximum vehicle count error was ±3-4%, while the errors in DT detectors were between -4% and zero, since DT technology does not over count vehicles.

In addition, in day 6, there is also one minute without data (7:46), and while computing results there was one minute in which very high flow was observed. It was minute 7:47. The evidences showed that the data of minute 7:46 somehow ended up added to the data of 7:47. For this reason, I segregate the data to each minute, dividing the values of minute 7:47.

On the other hand, there is no data of lane changes at minute 7:00 in day 6. This has to be corrected as well. In observing the video, it was apparent that the minute is not completely registered. During the part of the minute, which was registered, there were no lane changes. Thus, I assume that there are no lane changes during that minute.

There is some loss of cars between ETD 13 (PK 4,73) and ETD 12(PK 4,21). In the incidents reported, the vehicle count from the 13 ETD(DT) detector for day 7 was malfunctioning and approximately 28% of the cars were lost (Soriguera & Sala, 2013). There is also a loss of vehicles in the simple loop detector, but fortunately this error is almost negligible, yet it is worth mentioning. The error can be seen while plotting cumulative curves of vehicle count in both sections, with a shifting of free flow travel time, **Figure 9**. Because ETD12 is downstream, its cumulative curve should be underneath the one of the detector ETD13. The fact that the placement of the curves is the other way around indicates that there is an error. After correcting this drift error, the resultant new graph is **Figure 10**, where there is no significant difference between both cumulative curves.

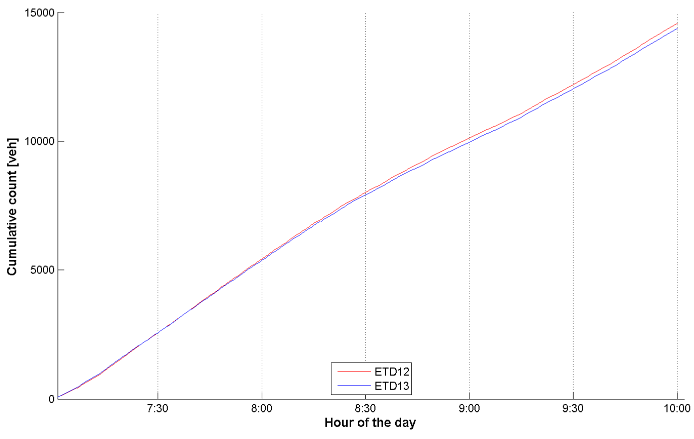

Figure 34 – Cumulative vehicle count for day 7

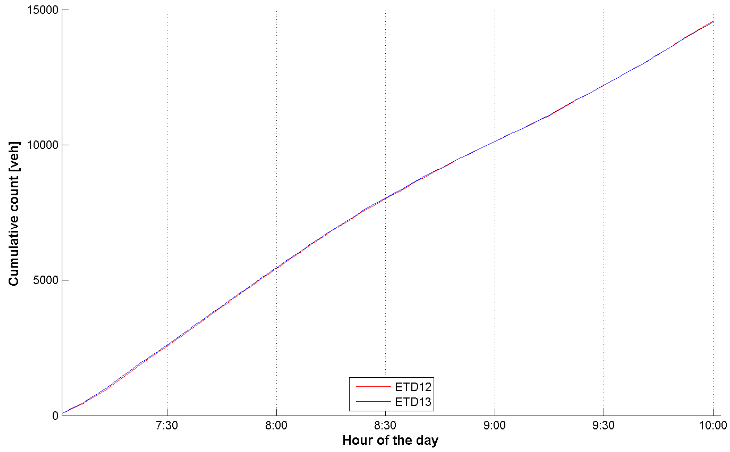

Figure 35 – Cumulative vehicle count for day 7 after correcting error

To see the magnitude of the error, I made a simple comparison of the difference between the initial values and the corrected ones. In total through all the 3 hours of experiment, only 171,824 cars where lost: 1,181% of the total of cars. Since the error is so small, we cannot know if it is in the detector ETD13(S) or ETD12. Thus, there is no need to correct the data on detector ETD13(S). The following table contains the vehicle count for each minute for the detector ETD13 and the cumulative values. It also shows the results of the correction of the drift error ε and the error itself for each minute and cumulative.

$$\varepsilon_i = \frac{N_{i,T}}{N_{Ref_i,T}}$$

$N_{i,T}$ are the cumulative number of cars in ETD13 and the $N_{Ref\,i,T}$ are the cumulated vehicles in ETD12 during the same period of time T=1min. (Janot, 2013)

Table 10 – Details of the error in ETD13

	initial		corrected		error							
Time	minute	cum	minute	cum	for each minute				cumulative			
7.01	69	69	70.107	70.107	1.107	cars	1.58	%	**1.107**	cars	**1.579**	%
7.02	65	134	66.043	136.150	1.043	cars	1.58	%	**2.150**	cars	**1.579**	%
7.03	73	207	74.171	210.322	1.171	cars	1.58	%	**3.322**	cars	**1.579**	%
7.04	66	273	67.059	277.381	1.059	cars	1.58	%	**4.381**	cars	**1.579**	%
7.05	66	339	67.059	344.440	1.059	cars	1.58	%	**5.440**	cars	**1.579**	%
(…)	(…)	(…)	(…)	(…)	(…)		(…)		(…)		(…)	
9.55	83	13996	83.223	14166.797	0.223	cars	0.27	%	**170.797**	cars	**1.206**	%
9.56	81	14077	81.217	14248.014	0.217	cars	0.27	%	**171.014**	cars	**1.2**	%
9.57	67	14144	67.180	14315.194	0.180	cars	0.27	%	**171.194**	cars	**1.196**	%
9.58	75	14219	75.201	14390.395	0.201	cars	0.27	%	**171.395**	cars	**1.191**	%
9.59	79	14298	79.212	14469.607	0.212	cars	0.27	%	**171.607**	cars	**1.186**	%
10.00	81	14379	81.217	14550.82	0.217	cars	0.27	%	**171.824**	cars	**1.181**	%

A.3 Compliance of the drivers

The following contour plots show the compliance level of dynamic speed limits (DSL) in the both sections with enforcement (radar). Every minute observation is classified into a cell depending on its sectional occupancy and DSL. Besides, each minute is classified in three different colors depending on the relation between DSL and average sectional speed. Each cell on the contour plot is colored according to the majority color of the values it contains. The conditions are as follow:

- Red: Vm > 10km/h +SL (speeding)
- Yellow: Vm < SL – 10km/h (ineffective SL)
- Green: SL – 10km/h < Vm < 10km/h + SL

The percentage in each cell indicates the percentage of the dominant color over all minutes related to the cell, which number is also plotted in the cell. This plots are for more than one section, for this reason the number of minutes is higher than 180 per day.

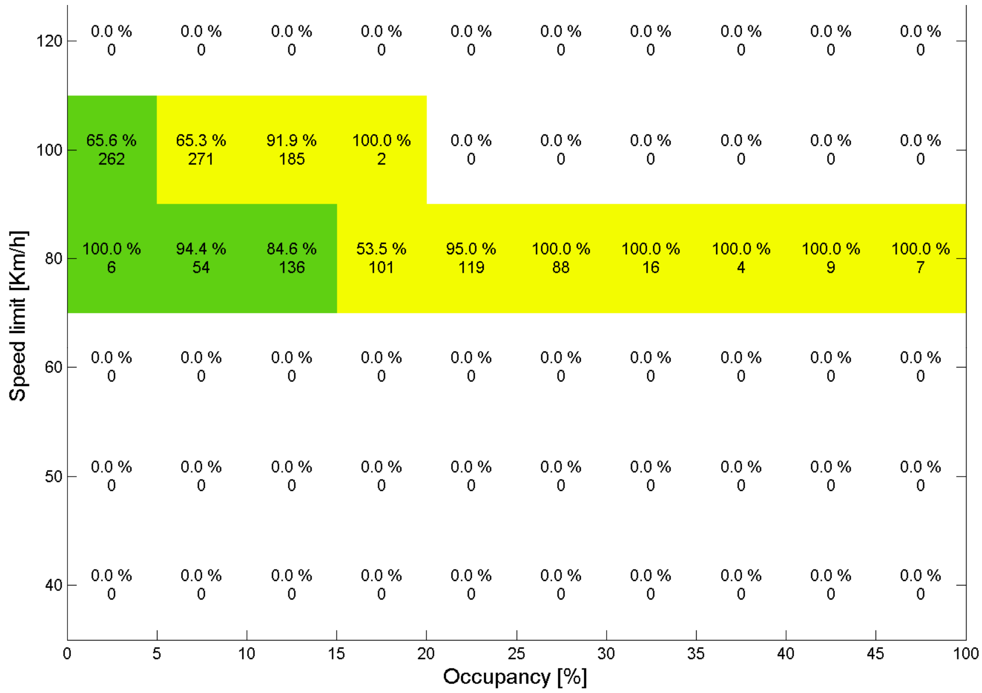

Figure 36 – Compliance contour plot day 5 with enforcement

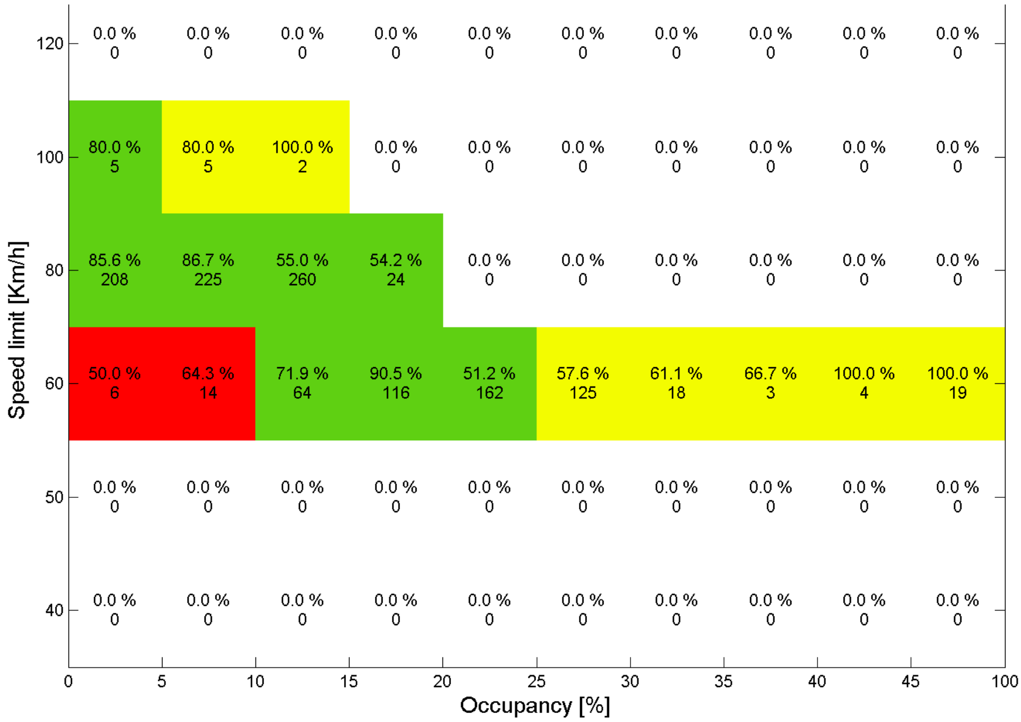

Figure 37 – Compliance contour plot day 6 with enforcement

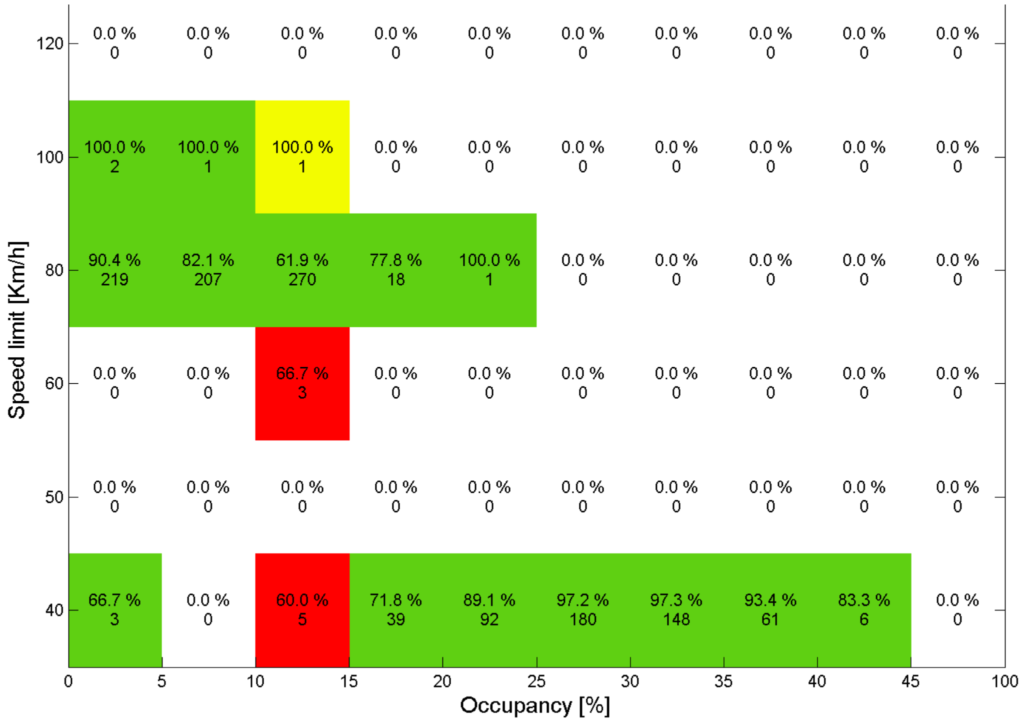

Figure 38 – Compliance contour plot day 7 with enforcement

ANNEX B : Congested and uncongested periods

As the background values does not influence the relative difference between minutes, I have "played" with different values of background flow and background occupancy, in the interest of seeing better small perturbation. This is shown in **Figure 39** for day 6 and **Figure 42** for day 5. The pointed ovals show some perturbations in traffic and the bigger oval indicates where traffic congestion starts.

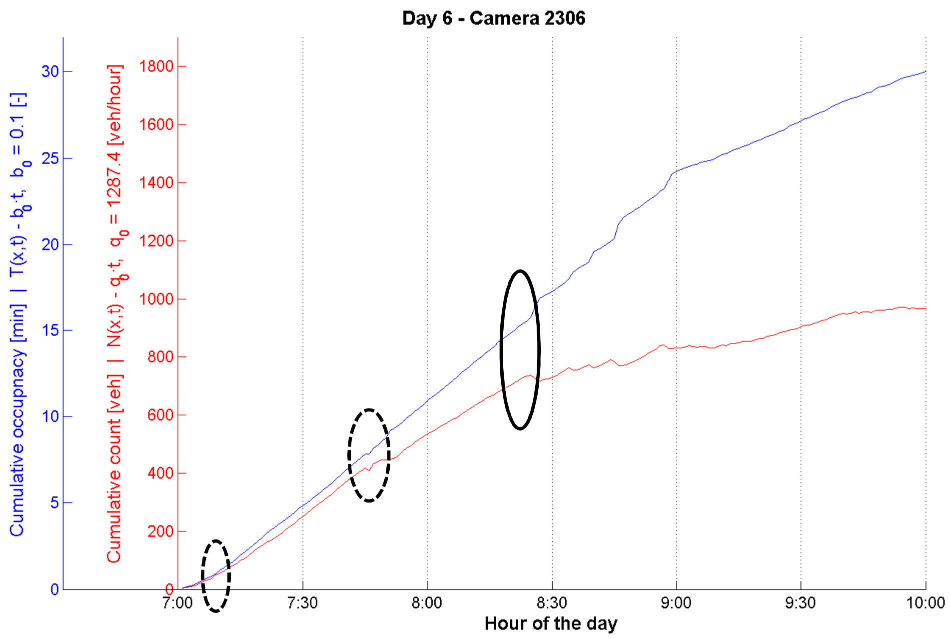

Figure 39 – Cumulative curves day 6, with lower background values

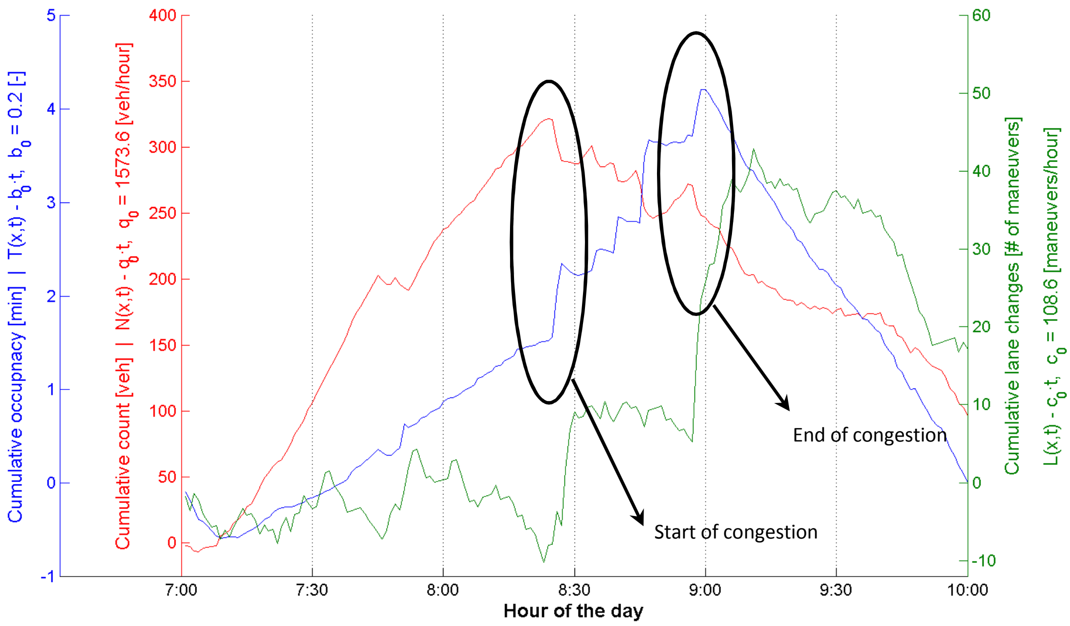

Figure 40 – Start and end of congestion in day 6

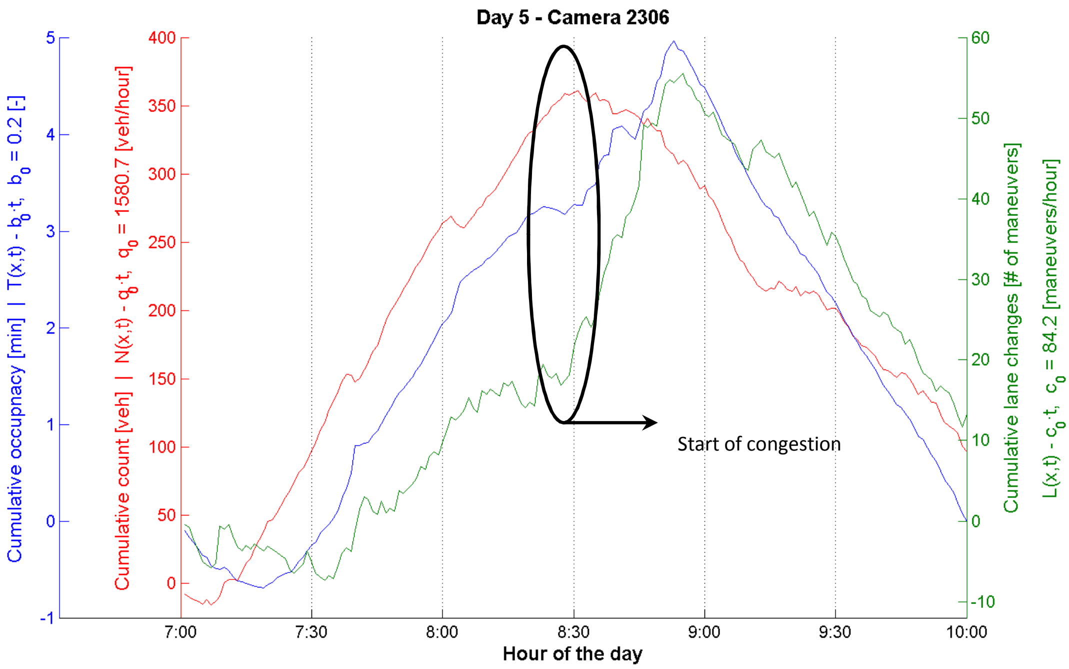

Figure 41 – Congestion start on day 5

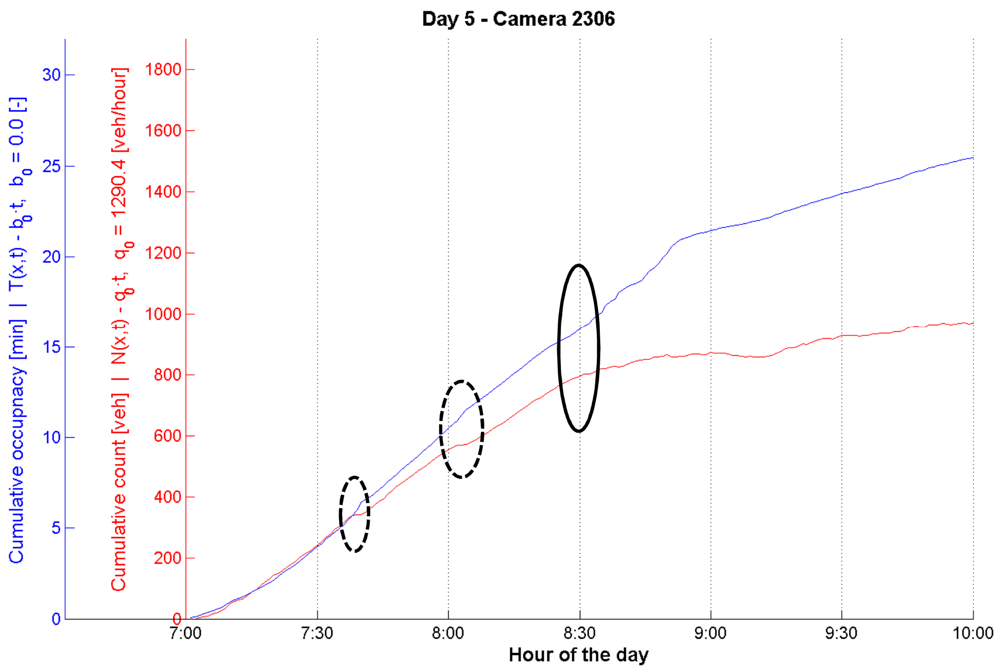

Figure 42 – Cumulative curves day5, with lower background values

The following graphs present the average lane speed for each lane and for each day.

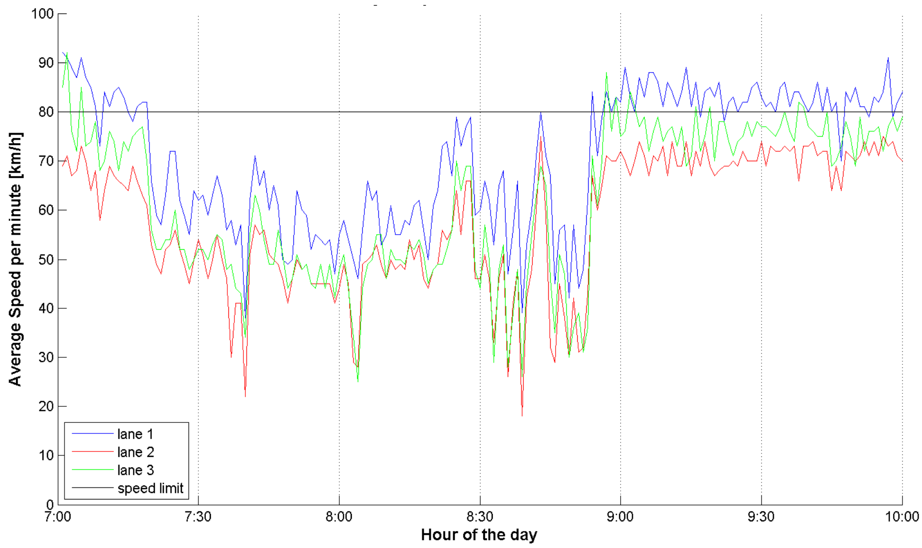

Figure 43 – Lane speeds across time, day 5

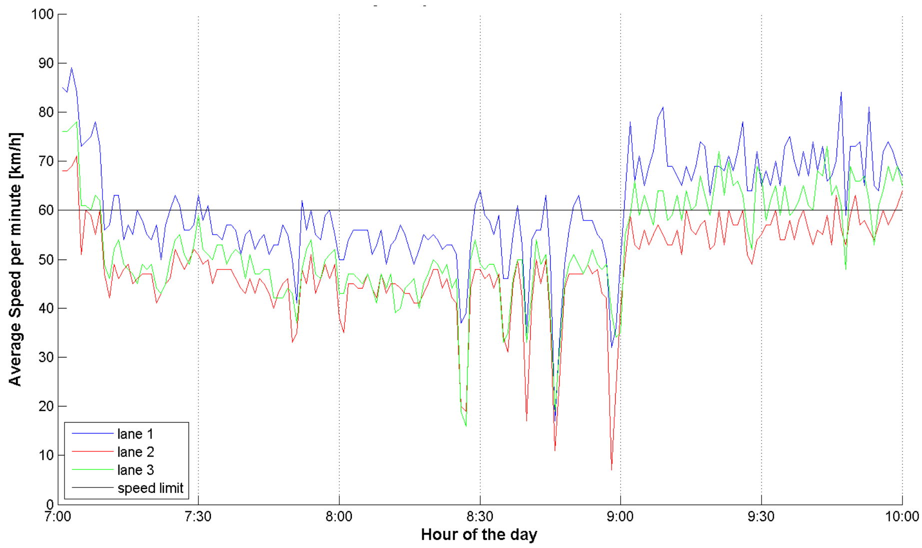

Figure 44 – Lane speeds across time, day 6

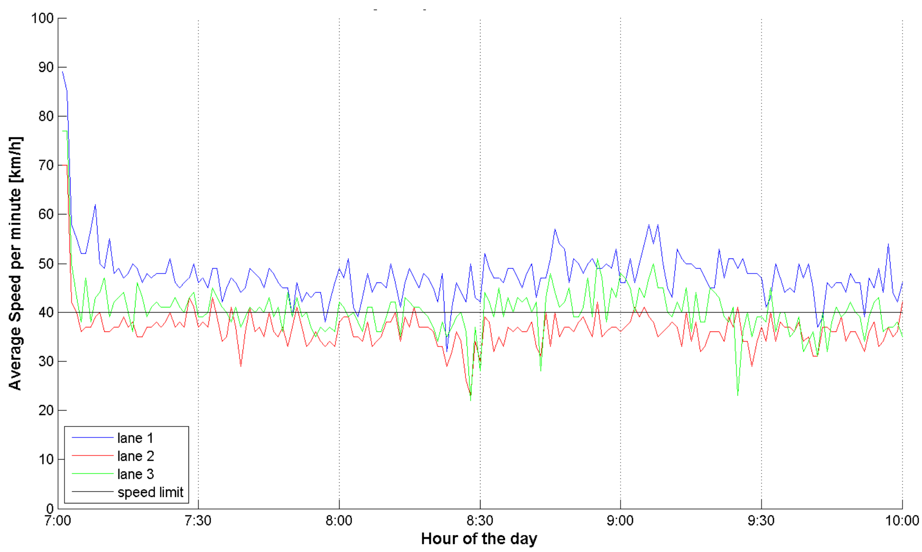

Figure 45 – Lane speeds across time, day 7

ANNEX C : Stationary Periods

Annex C.1 Graphs

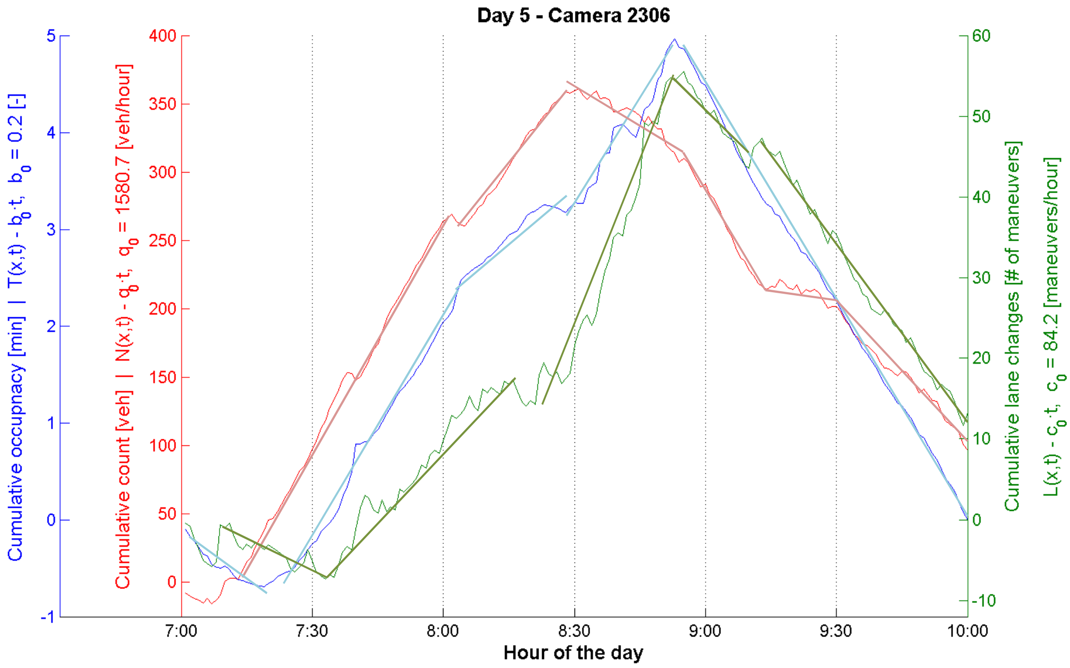

Figure 46 – Visual definition of stationary periods for day 5

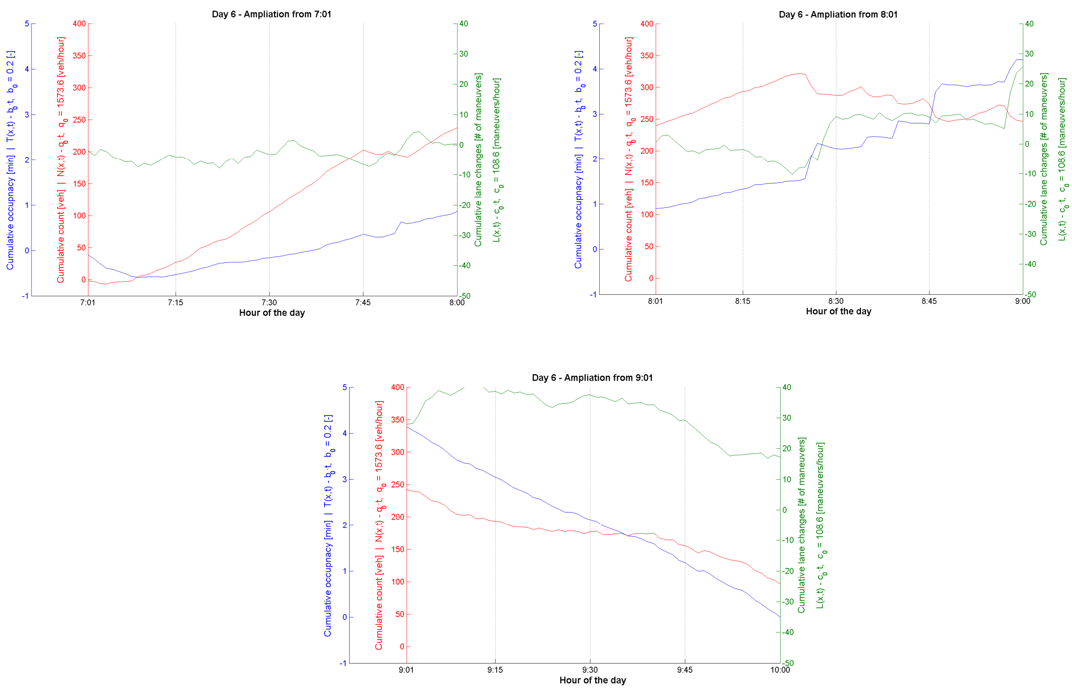

Figure 47 – Cumulative curves for each hour. Day6

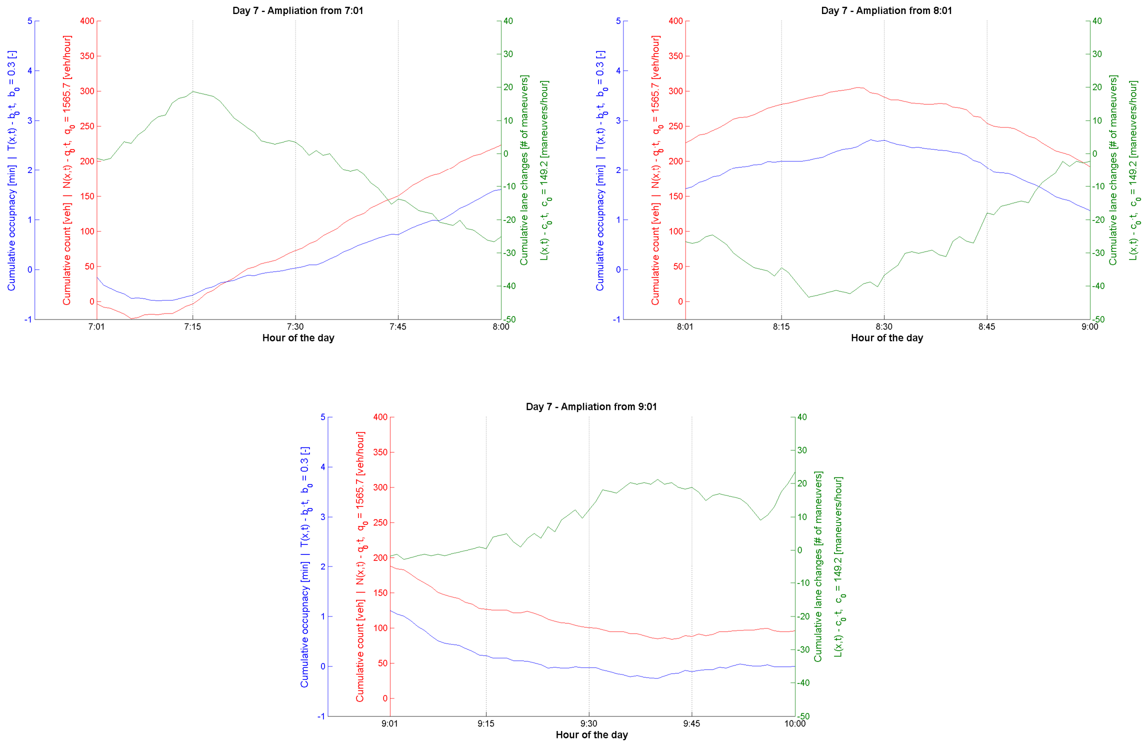

Figure 48 – Cumulative curves for each hour. Day7

Annex C.2 Tables

Table 11 – List of stationary periods for each day:

		Day 5	Day 6	Day 7
SP_1	time	7:01-7:08	7:01-7:08	7:03-7:06
	qf [veh/h]	4447.50	4672.50	3960.00
	lch [lch/h/km]	391.30	586.96	1956.52
	occf [%]	12.71	15.00	21.17
SP_2	time	7:13-7:27	7:12-7:23	7:07-7:12
	qf [veh/h]	5680.00	5520.00	4910.00
	lch [lch/h/km]	591.30	1000.00	2347.83
	occf [%]	19.84	24.83	27.00
SP_3	time	7:28-7:38	7:24-7:34	7:13-7:16
	qf [veh/h]	5923.636364	5847.27	5625.00
	lch [lch/h/km]	853.7549405	1280.63	1695.65
	occf [%]	25.7575758	23.94	32.17
SP_4	time	7:39-7:40 C	7:35-7:45	7:17-7:23
	qf [veh/h]	4230.00	5880.00	5794.29
	lch [lch/h/km]	1304.35	569.17	521.74
	occf [%]	40.83	26.09	32.33
SP_5	time	7:43-7:48	7:46-7:53 C	7:25-7:33
	qf [veh/h]	6010.00	4597.50	5433.33
	lch [lch/h/km]	608.70	1630.43	985.51
	occf [%]	25.06	25.42	30.11
SP_6	time	7:49-8:00	7:54-8:00	7:34-7:44
	qf [veh/h]	5720.00	5751.43	5672.73
	lch [lch/h/km]	1086.96	670.81	521.74
	occf [%]	26.11	25.71	33.27
SP_7	time	8:02-8:05 C	8:01-8:23	7:45-7:57
	qf [veh/h]	4485.00	5371.30	5589.18
	lch [lch/h/km]	1043.48	703.21	922.96
	occf [%]	29.67	25.03	33.30
SP_8	time	8:06-8:10	8:24-8:30 C	7:58-8:08
	qf [veh/h]	5544.00	3874.32	5509.09
	lch [lch/h/km]	939.13	2384.87	1043.48
	occf [%]	22.67	32.50	33.27
SP_9	time	8:11-8:20	8:31-8:47 C	8:09-8:19
	qf [veh/h]	5592.00	4309.38	5187.27
	lch [lch/h/km]	678.26	951.65	664.03
	occf [%]	23.50	30.60	29.12
SP_10	time	8:21-8:28	8:48-8:56	8:20-8:28 C
	qf [veh/h]	5385.00	5186.67	4853.33
	lch [lch/h/km]	913.04	753.62	1565.22
	occf [%]	18.83	22.78	32.30
SP_11	time	8:29-8:39 C	8:57-9:00 C	8:29-8:41
	qf [veh/h]	4505.45	3570.00	4398.46
	lch [lch/h/km]	1565.22	3521.74	1846.15
	occf [%]	26.76	34.42	25.64

SP_12	*time*	8:44-8:53 C	9:01-9:12	8:42-8:47
	q_f [veh/h]	4176.00	3985.00	3850.00
	lch [lch/h/km]	1565.22	1608.70	2086.96
	occ_f [%]	28.60	14.11	20.94
SP_13	*time*	8:55-9:10	9:13-9:22	8:49-8:56
	q_f [veh/h]	3851.25	4458.00	3885.00
	lch [lch/h/km]	358.70	678.26	2152.17
	occ_f [%]	10.67	15.57	21.25
SP_14	*time*	9:14-9:26	9:23-9:40	8:57-9:08
	q_f [veh/h]	4675.38	4636.67	3770.00
	lch [lch/h/km]	321.07	898.55	1347.83
	occ_f [%]	12.95	16.74	20.19
SP_15	*time*	9:27-10:00	9:41-10:00	9:16-9:40
	q_f [veh/h]	4132.94	4017.00	4392.00
	lch [lch/h/km]	368.29	495.65	1732.17
	occ_f [%]	11.34	14.23	25.92
SP_16	*time*			9:41-9:52
	q_f [veh/h]			4879.98
	lch [lch/h/km]			1043.48
	occ_f [%]			30.06

Table 12 – Stationareity analisis for periods defined for day 5

C	O	LCH	max deviation C		max deviation Occ		D	Min out of rang
24.708	***0.127***	***0.750***	18.667	29.667	0.090	0.160	8	0
31.556	***0.198***	***1.133***	26.000	33.667	0.140	0.260	15	2
32.909	***0.258***	***1.636***	30.000	35.333	0.227	0.333	11	1
23.500	***0.408***	***2.500***	21.333	25.667	0.343	0.473	2	0
33.389	***0.251***	***1.167***	30.667	36.333	0.203	0.273	6	0
31.778	***0.261***	***2.083***	31.000	33.333	0.237	0.290	12	0
24.917	***0.297***	***2.000***	21.333	29.333	0.237	0.350	4	0
30.800	***0.227***	***1.800***	29.000	33.000	0.213	0.247	5	0
31.067	***0.235***	***1.300***	28.667	32.667	0.207	0.267	10	0
29.917	***0.188***	***1.750***	27.667	31.667	0.163	0.223	8	1
25.030	***0.268***	***3.000***	18.000	29.667	0.183	0.447	11	2
23.200	***0.286***	***3.000***	14.667	31.000	0.147	0.427	10	4
21.396	***0.107***	***0.688***	17.667	28.667	0.083	0.170	16	2
25.974	***0.129***	***0.615***	19.333	32.000	0.090	0.163	13	0
22.961	***0.113***	***0.706***	16.667	29.667	0.077	0.157	34	0

Table 13 – Stationareity analisis for periods defined for day 6

C	O	LCH	max deviation C		max deviation Occ		D	Min out of rang
25.958	***0.150***	***1.125***	23.000	29.000	0.113	0.197	8	0
30.667	***0.248***	***1.920***	27.667	33.667	0.217	0.267	12	0
32.485	***0.239***	***2.455***	31.333	34.333	0.223	0.257	11	0
32.667	***0.261***	***1.091***	31.333	35.667	0.240	0.303	11	0
26.875	***0.262***	***3.125***	10.667	45.667	0.060	0.477	8	1
31.952	***0.257***	***1.286***	30.333	33.667	0.243	0.287	7	0
29.841	***0.250***	***1.348***	27.333	32.333	0.223	0.297	23	0
21.524	***0.325***	***4.571***	7.667	27.000	0.177	0.720	7	5
23.941	***0.306***	***1.824***	6.667	31.667	0.183	0.937	17	3
28.815	***0.228***	***1.444***	23.333	31.667	0.200	0.293	9	1
19.833	***0.344***	***6.750***	10.000	25.000	0.213	0.513	4	3
22.139	***0.141***	***3.083***	17.667	26.667	0.100	0.193	12	2
24.767	***0.156***	***1.300***	21.333	29.000	0.123	0.190	10	0
25.759	***0.167***	***1.722***	20.333	29.667	0.127	0.223	18	1
22.317	***0.142***	***0.950***	17.000	30.333	0.097	0.230	20	2

Table 14 – Stationareity analisis for periods defined for day 7

C	O	LCH	max deviation C		max deviation Occ		D	Min out of rang
22.000	***0.212***	***3.750***	19.667	24.333	0.190	0.233	4	0
27.278	***0.270***	***4.500***	26.000	29.667	0.243	0.290	6	0
31.250	***0.322***	***3.250***	29.333	33.333	0.310	0.353	4	0
32.190	***0.323***	***1.000***	30.000	34.667	0.300	0.360	7	0
30.185	***0.301***	***1.889***	28.000	32.333	0.277	0.323	9	0
31.515	***0.333***	***1.000***	29.333	34.000	0.313	0.363	11	0
31.051	***0.333***	***1.769***	28.667	34.000	0.270	0.373	13	0
30.606	***0.333***	***2.000***	27.667	32.333	0.287	0.367	11	0
28.818	***0.291***	***1.273***	26.667	30.667	0.270	0.337	11	1
26.963	***0.323***	***3.000***	19.667	30.333	0.297	0.357	9	0
24.436	***0.256***	***3.538***	22.000	27.667	0.227	0.303	13	1
21.389	***0.209***	***4.000***	17.000	24.667	0.170	0.257	6	0
21.583	***0.213***	***4.125***	19.333	24.333	0.187	0.233	8	0
20.944	***0.202***	***2.583***	18.333	25.000	0.160	0.243	12	0
24.400	***0.259***	***3.320***	21.333	28.333	0.217	0.303	25	2
27.111	***0.301***	***2.000***	23.667	30.333	0.257	0.330	12	0

Annex C.3 Speed differences in free-flow periods

The following tables present the speed characteristics for all minutes belonging to the "two groups of speeds" in uncongested branch. They t-test column presents the p-value, which is the probability both groups of speeds are similar. As the p-value is smaller than 0.05 for all three days, it can be stated that the SP appertain to different "groups".

Table 15 – T-Student Test for day 5

Day 5	Vmax	Vmin	Vm	T.test
Vsup	84.67	70.67	76.36287	1.5E-46
Vinf	69	43.33	53.68927	

Table 16 – T-Student Test for day 6

Day 6	Vmax	Vmin	Vm	T.test
Vsup	78.33	53.33	62.91667	6.4E-40
Vinf	53	42.67	49.23077	

Table 17 – T-Student Test for day 7

Day 7	Vmax	Vmin	Vm	T.test
Vsup	50	37.33	41.6841	0.0000052
Vinf	36.67	33	35.09524	

The following graphs are the flow-occupancy diagrams for each day. In each graph only the minute aggregation data for the minutes that pertain to stationary periods are represented. Colors indicate is the minutes pertain to a congested SP or a uncongested SP. Also the speed of the represented minutes can be distinguished by the color.

The „limiting speed“ is 70km/h for day 5; 55km/h for day 6 and 35km/h for day 7.

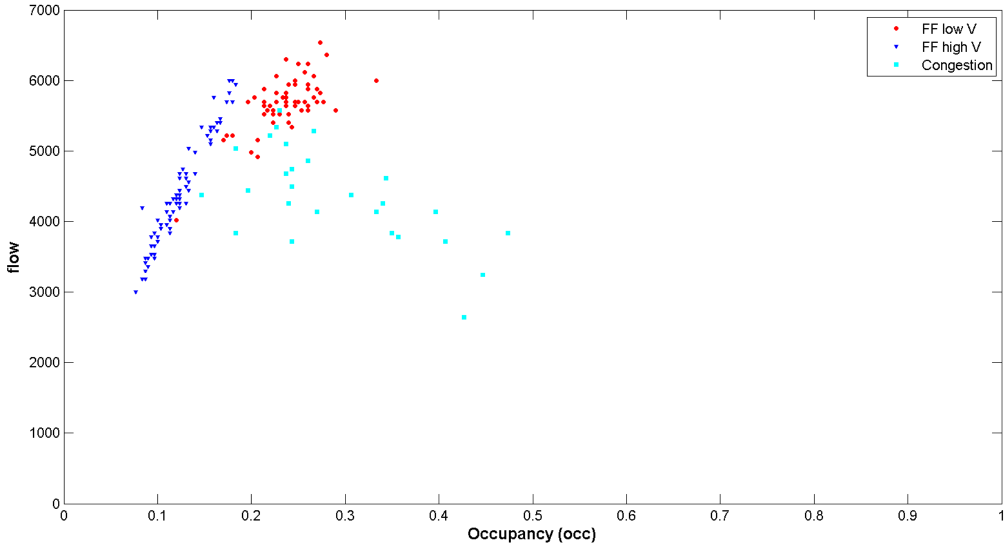

Figure 49 – Sectional flow vs average occupancy data agregated in minutes. Day 5.

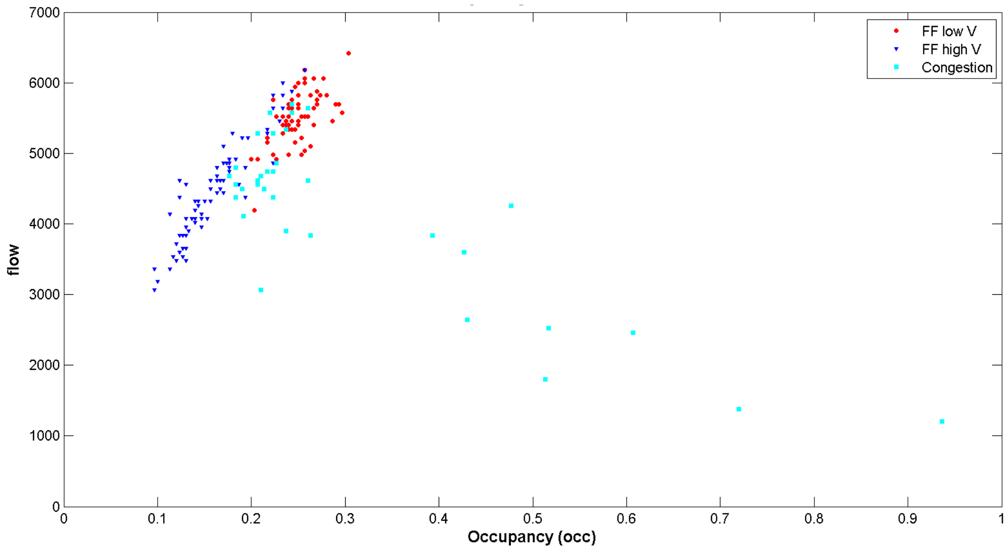

Figure 50 – Sectional flow vs average occupancy data agregated in minutes. Day 6.

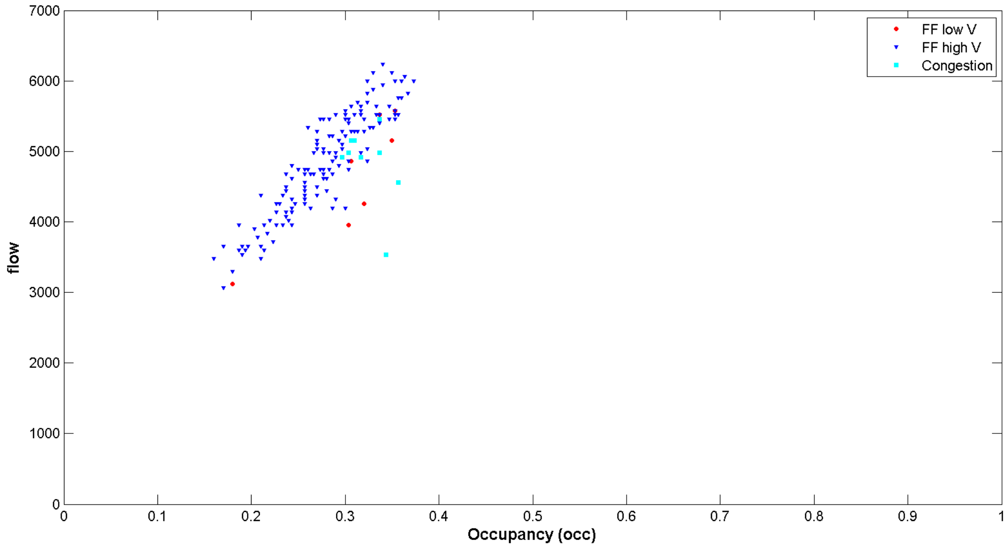

Figure 51 – Sectional flow vs average occupancy data agregated in minutes. Day 7.

Tables 18 to 21 summarize the average values for each stationary period corresponding to each of the groups.

Table 18 – Stationary periods of day 5 with higher average speed than 70 km/h

Flow	Occupancy	Lane changing rate	Speed	Duration
4447.5	0.127	391.3	78.7	8
3851.2	0.107	358.7	76.4	16
4675.4	0.129	321.1	75.8	13
4132.9	0.113	368.3	76.6	34

Table 19 – Stationary periods of day 5 arround capacity

Flow	Occupancy	Lane changing rate	Speed	Duration
5680.0	0.198	591.3	64.2	15
5923.6	0.258	853.8	52.6	11
6010.0	0.251	608.7	55.3	6
5720.0	0.261	1087.0	48.8	12
5544.0	0.227	939.1	53.6	5
5592.0	0.235	678.3	52.3	10
5385.0	0.188	913.0	63.8	8

Table 20 – Stationary periods of day 6 with higher average speed than 55 km/h

Flow	Occupancy	Lane changing rate	Speed	Duration
4672.5	0.150	587.0	70.6	8
3985.0	0.141	1608.7	61.9	12
4458.0	0.156	678.3	62.4	10
4636.7	0.167	898.6	62.6	18
4017.0	0.142	495.7	64.1	20

Table 21 – Stationary periods of day 6 arround capacity

Flow	Occupancy	Lane changing rate	Speed	Duration
5520.0	0.248	1000.0	50.3	12
5847.3	0.239	1280.6	53.4	12
5880.0	0.261	569.2	49.7	11
5751.4	0.257	670.8	50.4	7
5371.3	0.250	703.2	47.6	23
5186.7	0.228	753.6	50.7	9

ANNEX D: Homogenization

Here can be found the graphs to which section 5.2 of this Bachelor Thesis makes reference.

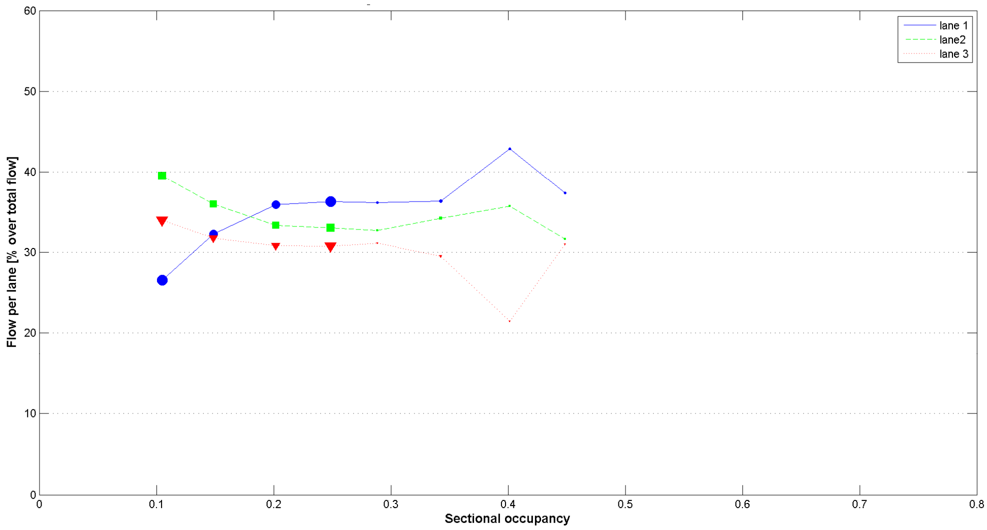

Figure 52 – Percentage flow for each lane. Day 5

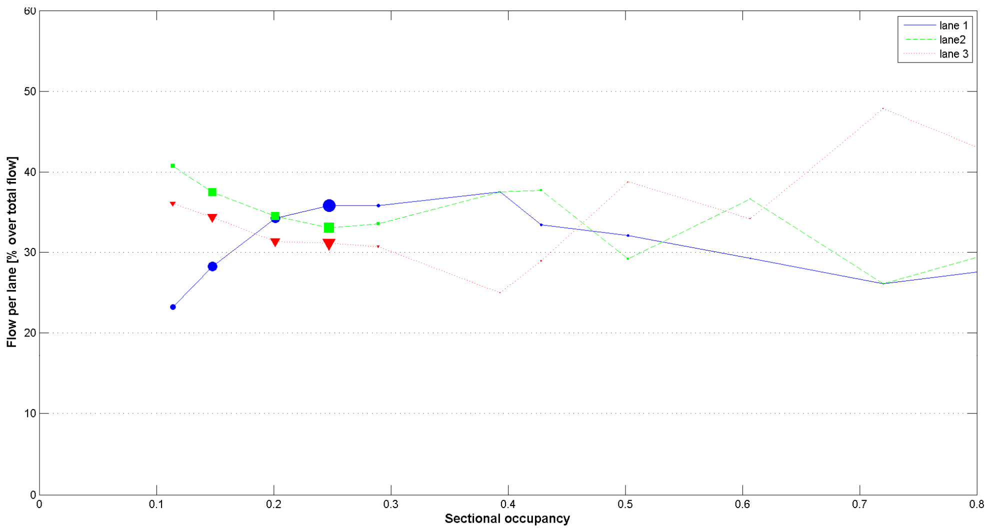

Figure 53 – Percentage flow for each lane. Day 6

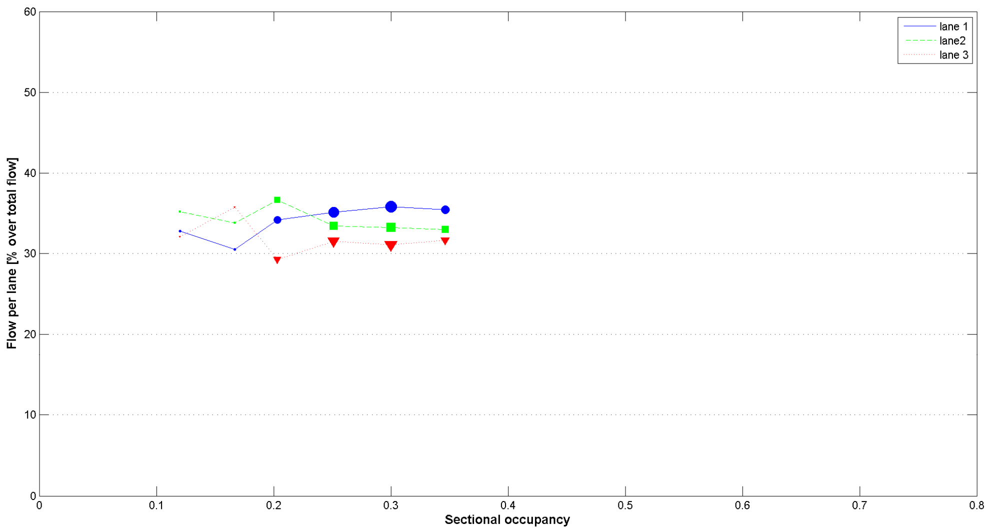

Figure 54 – Percentage flow for each lane. Day 7

Table 22 – Sectional data for occupancy bins.

			Day 5					Day 6					Day 7				
Bins			Occupancy	Flow	Lane Changes	Speed	# min	Occupancy	Flow	Lane Changes	Speed	# min	Occupancy	Flow	Lane Changes	Speed	# min
0.075	**to**	**0.125**	0.105	65.036	0.727	77.285	55	0.114	61.500	1.500	68.139	12	0.120	67.000	1.500	78.000	2
0.125	**to**	**0.175**	0.149	83.290	1.194	73.312	31	0.148	71.171	1.634	64.057	41	0.167	56.667	4.000	45.778	3
0.175	**to**	**0.225**	**0.202**	**90.516**	**2.000**	**59.774**	**31**	0.201	81.116	2.209	53.791	43	0.203	62.261	3.087	44.130	23
0.225	**to**	**0.275**	**0.249**	**92.667**	**1.771**	**51.111**	**48**	**0.247**	**91.662**	**1.676**	**49.578**	**68**	0.251	75.000	3.259	41.877	54
0.275	**to**	**0.325**	**0.288**	**91.750**	**1.750**	**47.333**	**4**	**0.290**	**97.000**	**1.286**	**46.381**	**7**	**0.300**	**85.227**	**2.303**	**40.611**	**66**
0.325	**to**	**0.375**	0.343	74.000	3.000	39.667	6						**0.347**	**92.750**	**1.781**	**38.813**	**32**
0.375	**to**	**0.425**	0.402	65.500	2.500	33.833	2	0.393	64.000	4.000	29.667	1					
0.425	**to**	**0.475**	0.449	54.000	4.000	32.333	3	0.428	52.000	4.500	34.500	2					
0.475	**to**	**0.525**						0.502	47.667	6.000	29.444	3					
0.525	**to**	**0.575**															
0.575	**to**	**0.625**						0.607	41.000	3.000	28.333	1					
0.625	**to**	**0.675**															
0.675	**to**	**0.725**						0.720	23.000	6.000	25.333	1					
0.725	**to**	**0.775**															
0.775	**to**	**0.825**															
0.825	**to**	**0.875**															
0.875	**to**	**0.925**															
0.925	**to**	**0.975**						0.937	20.000	0.000	15.667	1					

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