

EFFECTS OF VARIABLE SPEED LIMIT STRATEGIES ON A METROPOLITAN HIGHWAY

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ABSTRACT

The objective of this Thesis is to understand the situation of a catalan highway with VSL strategies through empirical data of one day. It will be done using standard traffic tools to make the congested and uncongested states analysis. The Thesis will involve: visual identification of congested areas, bottleneck detection and diagnostic, identification of fundamental diagrams, lane density and speed distribution and comparison between speed limits and measured speeds.

In addition, it will give recommendations and establish the basis for a future set of experiments to investigate VSL strategies in deep.

The main findings are the detection of five bottlenecks, many lane changes near the ramps and the change of occupancy distribution between lanes in congested periods. After a careful and detailed analysis of the data we can conclude that VSL is not as effective as it should be. That is caused by the algorithm it uses and the fact that drivers disobey speed limits.

INTRODUCTION

Traffic congestion close to big cities is one of the biggest problems that nowadays administrations have to deal with. That is why several traffic strategies are implemented and studied in highways around the world. One of the most debated and applied traffic strategies are Variable Speed Limit (VSL).

VSL strategies are used especially in Europe and EEUU highways close to big cities with lots of ramps. They can be used individually or in combined way with other strategies. VSL strategies aim to prevent traffic congestion, decrease pollution emissions, reduce vehicular crashes, avoid lane changes and harmonize flow within lanes. However, there are not many scientific proofs or evidence that supports all these benefits.

The objective of this thesis is to analyze a site where VSL strategies are implemented. The study is based on the measured data in a highway during an entire day, the highway (B-23). It is situated in the west side of Barcelona and only the southbound direction is studied. In order to understand the current situation of the highway, the thesis focuses on the following tasks: bottlenecks detection and diagnostic, capacity estimations, travel time analysis, traffic oscillations, and comparison between speed limits and measured speeds.

Five bottlenecks are found in the highway. Three of them are diverge bottlenecks, another one a merge bottleneck and one bottleneck is created in a traffic light. We can conclude that almost all the congestion is created by the ramps. Moreover, people wait until last meters to change to another lane to take the off ramps. This creates many lane changes near the ramps that could aggravate the congested situations.

This thesis will first introduce the dataset, followed by a brief explanation of the errors found in the data and how they are solved. In the next section, a general overview of the data in the highway is shown: periods with high demand, contour plots and importance of the different ramps. The rest of the thesis is divided in three parts. The first part is based on the analysis of the uncongested data, where free flow speeds are presented and compared with speed limits. The second part presents the corridor capacities and it deals with bottleneck detection and diagnostic. Finally, the third part analyzes the congested data through travel time analysis, queues and comparison between speeds in different lanes and speed limits. In the last section, some conclusions and further research problems are presented.

DATA AND DATA ERRORS

This study is based on data collected on highway B23, which is located on the west side of Barcelona. Only the southbound direction (i.e., entering Barcelona) is studied. Ranging from KP 11.20 (Molins de Rei) to KP 0.37 (Barcelona Diagonal). The studied area has 10.83KM long, with 6 off ramps and 9 on ramps in between. For most part, there are three or four lanes, but two lane highway (one direction) also exist for short distances.

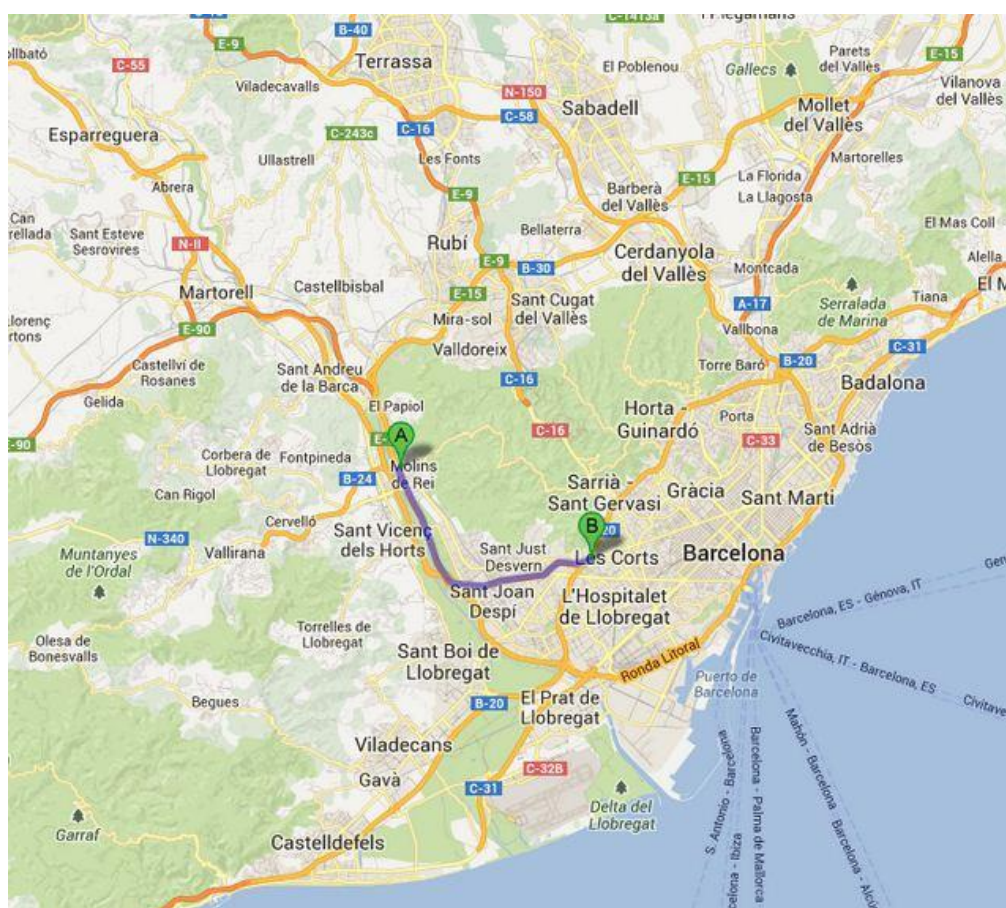


Figure 1a: Situation map of the studied highway MAP 1

The data is collected on date 12/12/2012 from 00:01 - 24:00 and it is aggregated data per minute. There are two sources of data:

- From Loop Detectors (ETD): They measure per minute and lane the different traffic variables: vehicle counting (#veh/min), time mean speed (Km/h) and occupancy (%). Four of the twenty-four loop detectors are simple, i.e. they do not measure speeds.

- Form VSL signs (PVV): The variable speed limits used in 18 VSL signs are recorded. They are allocated: 15 in the main truck, 2 VSL signs nearby off ramps and 1 VSL signs in one on ramp. The data provided by VSL signals corresponds to the speed displayed in the signals in each VSL signal per minute during all day.

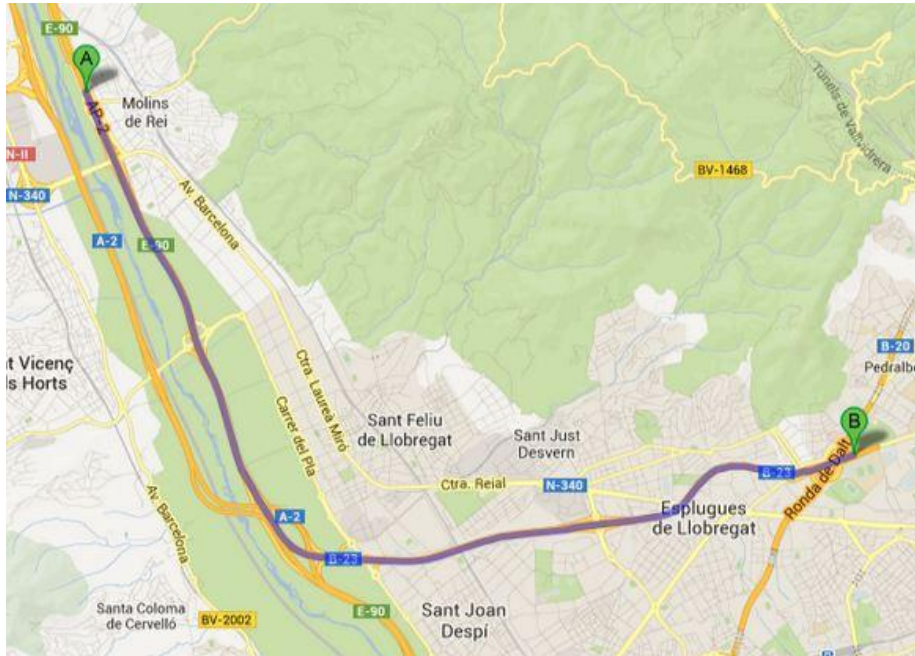


Figure 1b: Situation map of the studied highway MAP 2

Besides the previous monitoring equipment this area is also equipped with 12 TV cameras, 2 enforcement Radars, 3 License Plate Recognition (LPR) and 3 Variable Message Signs (VMS).

Note that the plots and figures which will be shown later only include data from the day hours, there are very few cars pass through the highway during the night hours (00h to 06h).

Great efforts have been paid to data cleansing, that is to discover and correct the mistakes contained in the original data. This part is essential to the whole research as the accuracy of the data used decides the quality and reliability of the conclusion drawn from this study. In general, there are three types of errors:

- “Pick Errors”¹. These errors have affected two traffic variables (Occupancy and Vehicle Counts) measured in few loop detectors. These errors consists of overestimated values that are impossible to happen in real conditions and they generate abnormal picks in time-traffic variables diagrams, e.g. occupancies larger than 100% or vehicle counts much greater than 50 veh/min per lane.
- “Zero Errors”². In randomly minutes the loop detector seems to fail or not save the data properly and it does not get any data, i.e. the vehicle counts, occupancy and speeds data have a value of zero in all lanes. That is why we called this error Zero Error. This error appears in 67% of the LDs and it happened during almost all day in 21% of the LDs. Zero Error is the most problematic and difficult solving error because it is very recurrent and it affected the three data types and the three lanes at the same time. In order to fix it we had to make some assumptions and use probabilistic approaches.

¹ For detailed information of how this error is fixed see Annex B.

² In Annex B the methodology used is explained in detail.

- “Drift Error”³. It only affects the vehicle counts data and it is an error that normally appears in real data. When a Loop Detector counts fewer vehicles than the amount that actually passes through we say that it has Drift Error. It could be easily detected comparing the cumulated plots of nearer LDs during a long period of time (hours). To fix it, we used a methodology based on distributing in a proportionally way the difference of cumulated vehicle counts between one reference loop detector and the mistaken one.

In some loop detectors two types of errors appear (Zero Error and Drift Error) and the fixing procedure has to be done in a combined way. For example, the identification of the Drift Error through comparing cumulated plots has to be done in a period of time without Zero Errors. Otherwise, the difference between the cumulated curves could be caused for the Zero Data and not for the Drift Error.

The data provided does not contain vehicle counts of the ramps and it was not possible to calculate and generate. That has been essential to make transformed cumulative diagrams through loop detectors with ramps in the middle.

OVERALL DATA ANALYSIS

Two periods can be clearly distinguished with higher demand, we define as rush hour periods (Figure 2):

- Morning 7:00 -10:00:
As we can see in Figure 2 the congestion appears in the morning between 7:00 and 10:00. During this period of time big areas of the highway are congested with occupancies above 20-30%. This period of time coincides with the time people go to work and kids go to school.
- Afternoon 17:00 – 20:00:
In this period of time appears a congested area near the entrance of Barcelona. It only appears around off ramp 14 (access to Barcelona beltway). Thus is due to the amount of vehicles that want to entrance the city and access to this beltway. In this part of the highway the number of lanes has been reduced from three to two. This time fits with the time people finish working and go home.

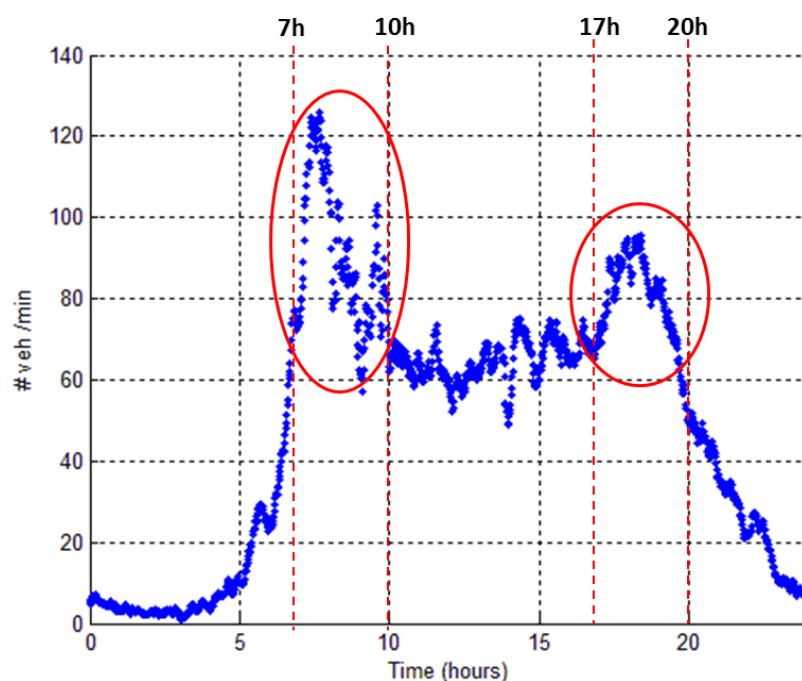


Figure 2: Distribution of the demand and identification of the rush hours

³ This methodology is thoroughly explained in Annex B.

There are more people that live outside Barcelona and work in the city than people that live in the city and work outside it. That is why the congestion in the morning is more important than the afternoon congestion where only the people who works outside the city and lives inside want to ingress on it.

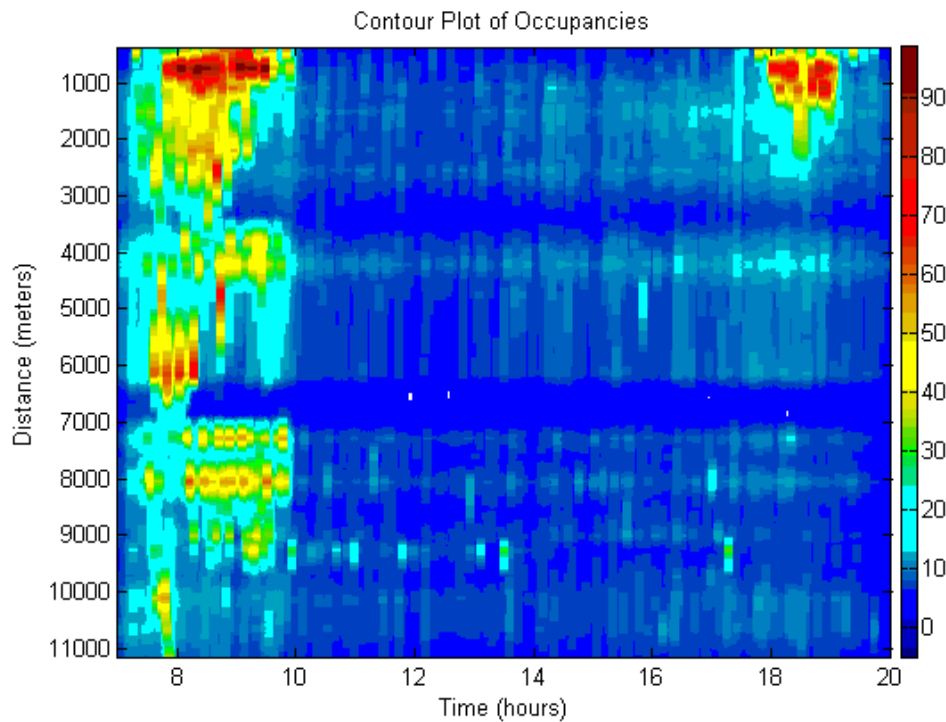


Figure 3: Contour Plot between 7:00 and 20:00

Besides the congestion times it is also important to see which parts of the highway are most demanded and where more vehicles enter or exit the highway. Figure 4 shows the relation between the total amount of vehicles that passes through each loop detector during all the day and the ramps in the highway.

The highway has mainly two important off ramps (S7 and S14) where around 60% of the vehicles go out. But it only has one important on ramp (E8).

The area of the highway between off ramp S7 and on ramp E8 has two lanes. Additionally, flows and occupancies are very low in this part because many vehicles use the off ramp (S7) and the on ramp (E8). Figure 3 reveals the low occupancy phenomenon (around KP 6.8).

Something similar happens in KP 3.5 between off ramp S11 and on ramp E12 but in this section the number of lanes remains unchangeable and the number of vehicles using these ramps is fewer. The vehicles going out in off ramp S11 represent around 25% of the highway flow, which is steady during the day. Large part of this flow is recovered downstream by on ramp E12 that provides fewer vehicles in the morning and more vehicles in the afternoon/night compared with vehicles using S11.

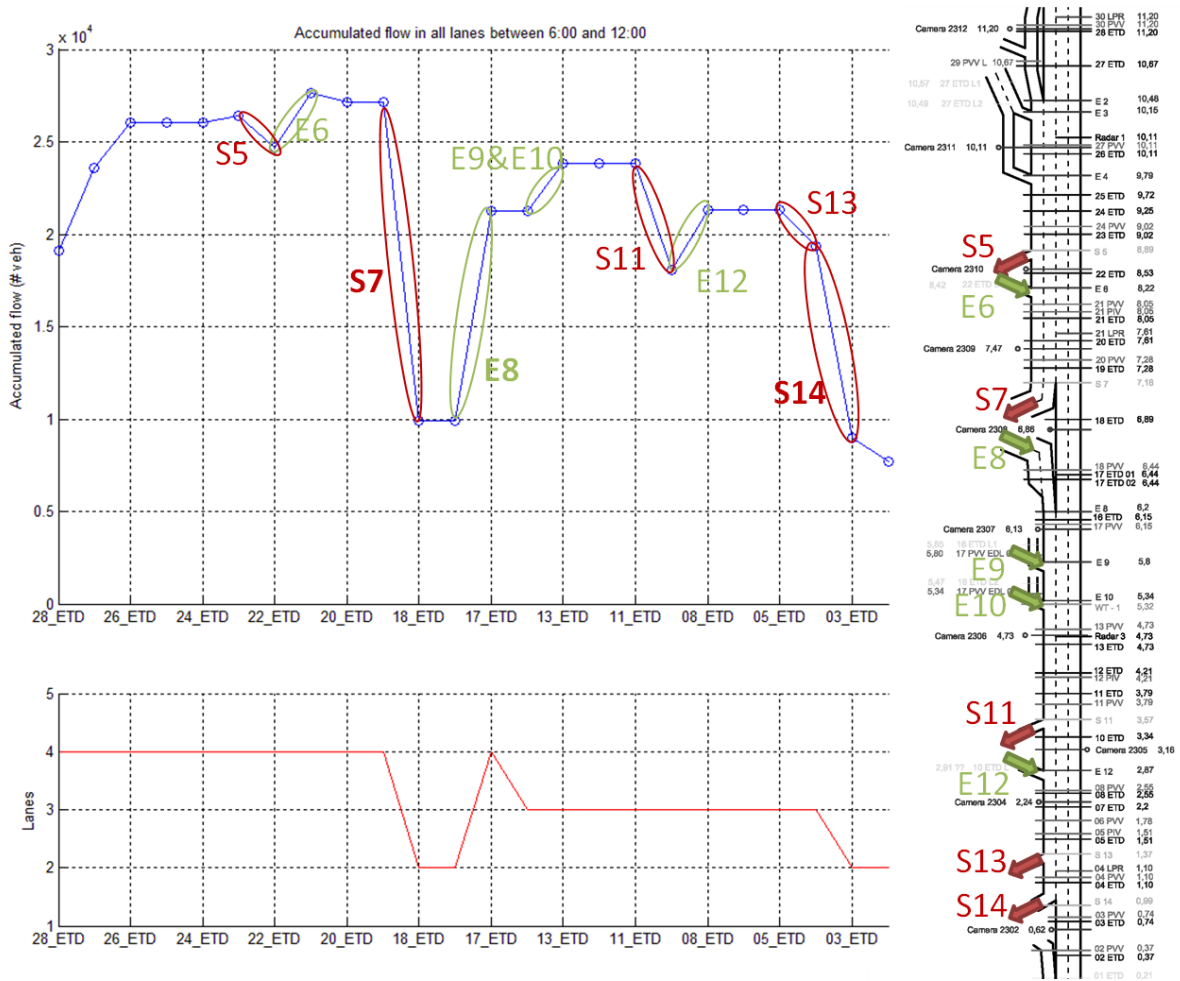


Figure 4: Total day flow in the different loop detectors and scheme of the highway

The first part of the highway (between 28 ETD and 18 ETD) always carries more vehicles than the second part reaching a total demand in a day of 70.000 vehicles. The speed limit without congestion corresponding to the first part is 100km/h while in the second part the normal speed limit is 80km/h. In the second part of the highway (between 18 ETD and 04 ETD) the total demand in a day reaches 62.000 vehicles. This does not entail any problems because in the first part of the highway there are in total 4 lanes, one lane more than in the second part. The last part of the highway (between 04 ETD and 02 ETD) is the transition between the highway and an urban street. It has only two lanes and it carries very few vehicles compared with other sections. The speed limit is between 50km/h and 60km/h.

UNCONGESTED TRAFFIC ANALYSIS

Three periods without congestion can be distinguished in the highway. The first one takes place during the night (00:00 – 07:00), this period is not important because the number of vehicles passing at that time is insignificant. The second one is after the morning rush hour and we have considered that it begins around 10:00 and it extends until second rush hour, it is the more demanding uncongested period. The last uncongested period begins at 20:00 and ends at midnight. Table 1 presents the range of flows that the highway has in the different periods of time.

Time periods	Flow (veh/h)
00:00 – 07:00 (Night)	0 – 300
10:00 – 19:00	3000 – 3600
20:00 – 24:00	600 – 1800

Table 1: Average flows in the different uncongested periods

During uncongested periods, VSL remains unchangeable being 100 km/h the speed limit for the first part of the highway and 80km/h for the second. There are two special speed limits near the entrance of Barcelona: 60km/h in KP 0.74 (03 ETD) and 50km/h in KP 0.37 (02 ETD).

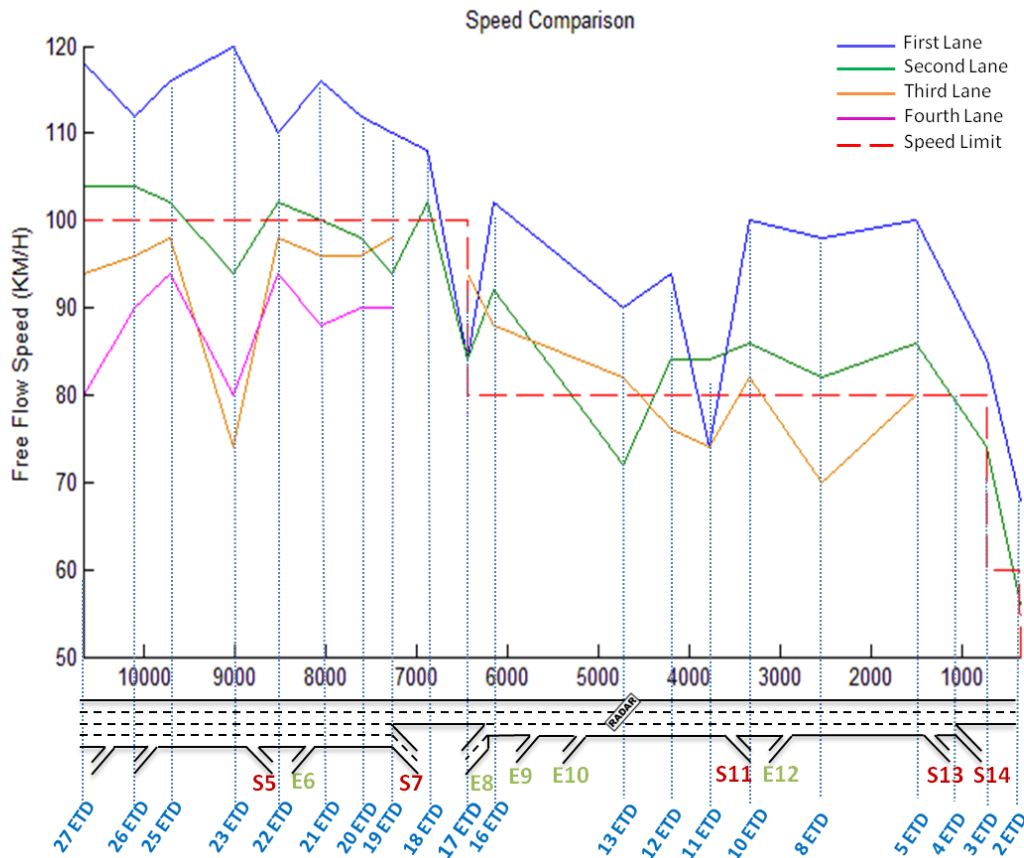


Figure 5: Free flow speed comparison with speed limits throughout the highway

The first lane (inner lane) is always the one with fewer vehicles but it is also the lane where vehicles travel faster with free flow speeds usually 10-20km/h above the speed limit. The second lane has speeds close to the speed limit. While in the other lanes people normally drive with speeds below the speed limit. Speeds in lane 3 are normally greater than in lane 4.

Regarding the lane occupancy the first lane is always the emptiest compared to the others. This occupancy is usually around 2-3% but between 16 ETD and 11 ETD the occupancy is around 5% due to the elimination of one lane. The occupancy in lane 2 is usually around 5% with some exceptions. The remaining lanes occupancy mainly varies between 5% and 15%.

	Free Flow Speed (km/h)					
	Lane 1	Lane 2	Lane 3	Lane 4	Average per LD	Speed Limit
02 ETD	68	56			62	50
03 ETD	84	74			78	60
05 ETD	100	86	80		88	80
08 ETD	98	82	70		82	80
10 ETD	100	86	82		90	80
11 ETD	74	84	74		78	80
12 ETD	94	84	76		84	80
13 ETD	90	72	82		80	80
16 ETD	102	92	88		96	80
17 ETD	84	84	94	78	86	80
18 ETD	108	102			106	100
19 ETD	110	94	98	90	98	100
20 ETD	112	98	96	90	98	100
21 ETD	116	100	96	88	100	100
22 ETD	110	102	98	94	102	100
23 ETD	120	94	74	80	92	100
25 ETD	116	102	98	94	102	100
26 ETD	112	104	96	90	100	100
27 ETD	118	104	94	80	98	100

Table 2: Free flow speeds per lane and average for all Loop Detectors

Lanes 3 and 4 by 23 ETD, the free flow speeds are extremely low compared to near locations, especially lane 3 with a free flow speed of 74km/h. This could be produced by lane changes of vehicles that want to take off ramp S5 but we cannot be certain that this is the reason. It could be also caused by an error of the loop detector measuring speeds, the speed of lane 3 should be lower than the speed of lane 2 and higher than the speed of lane 4 (similar with all nearby loop detectors). Yet, we are not able to explain this abnormal phenomenon because of the lack of information.

One of the most interesting sections is between off ramp S7 and on ramp E8 (19 ETD to 16 ETD). First of all, at 19 ETD location the vehicles have to prepare for the two-lane off ramp where a lot of trucks go out. In lane 3 the speeds are greater than in lane 2 because the third lane will be the fast lane of the off ramp. The slower vehicles that want to continue in the highway have to change to lane 2. This produces that the two pairs of lanes (1-2 and 3-4) behave like if they were in two different highways, being the lane 1 and 3 the fast lane and lane 2 and 4 the slow lane respectively. The main difference is that in lane 3 and 4 there are more vehicles and they have to travel slower with higher occupancies.

Going downwards there is the on ramp E8 with two lanes but only one is added to the highway. Moreover, the speed limit changes before the on ramp from 100km/h to 80km/h. This causes the smoothness of speeds in the main lanes of 17 ETD (lane 1 and 2) where free flow speeds are the same (84 km/h) but with different occupancies: 2-3% in lane 1 and 5% in lane 2. Loop detector 17 ETD is the only location where lane 1 does not have the highest speeds, this is due to the two lanes of the on ramp E8 (lane 3 and 4 of 17 ETD) that comes from another highway with speed limit of 100km/h and they are still reducing speed.

The vehicles reduce their speed near 13 ETD because there is an enforcement radar that controls the two fastest lanes. The drastically reduction of speed in lane 2 could be caused for the reaction of the drivers when

they see the radar panel. However, the free flow speed in lane 3 is greater due to the radar does not control that lane.

The first lane of 11 ETD has measures of very low speeds, with similar values of speeds in the third lane. That is why the free flow speed is the same (74km/h) in the first and third lane. This could be caused for a particular problem in that lane that makes drivers reduce speed, e.g. pothole. But it rather could be caused for a fail of the measuring equipment because the speeds in lane 1 before and after 11 ETD are around 20km/h more than there.

In the section between off ramp S11 and on ramp E12, the vehicles that want to take S11 are placed in the third lane. This produces that after the off ramp, the occupancy in the third lane is very low with similar values to lane 1 (2-4%) while in the second lane it is around 8%. The occupancy in the third lane is recovered after E12, where vehicles access to the highway through the third lane.

The off ramp S14 is one of the most demanded off ramps. That is why more than 50% of the vehicles approximate to this ramp traveling in the third lane (lane turned into off ramp).

CORRIDOR CAPACITIES

One important traffic characteristic of the highway is the capacity, maximum flow that can pass through one location. In order to determine the capacity, it is important to have the following scenario in the location we want to calculate: congestion upstream (full of vehicles) and uncongested state downstream (the vehicles can drive at free flow speed). This scenario is a reality when a bottleneck is activated in one location and downstream locations are not congested. Thus the flows measured in one loop detector downstream a bottleneck could merely be the capacity of the bottleneck upstream. Therefore, we cannot measure the capacity in one location if there is not a bottleneck.

That is why we calculate the bottleneck capacities that would be the corridor capacities. Moreover, we have used fundamental diagrams, besides calculating free flow speeds, for calculating the maximum flows measured in each loop detector.

FUNDAMENTAL DIAGRAMS

We have build for each loop detector the fundamental diagram⁴, differentiating the data of different lanes. Each data lane is plotted with a different color. Figure 6 shows one example of our fundamental diagrams, exactly from 12 ETD data.

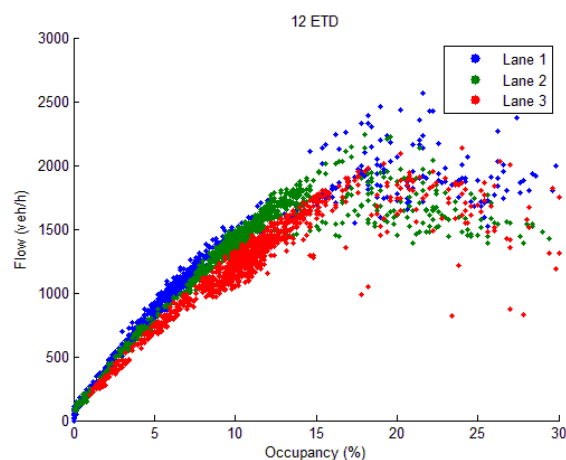


Figure 6: Fundamental diagram of 12 ETD

⁴ Annex D contains all the fundamental diagrams of all loop detectors.

These fundamental diagrams are created using directly the aggregated data per minute of vehicle counts and occupancies. Thus the maximum flows measured during all the day appear in the top of the diagram, but they do not represent the real capacity of the location. Table 3 presents the values of these maximum flows measured during the entire day (we take as a reference value where the density of points begins to be high).

Table 3: Maximum flows measured (veh/h per lane)

	Lane 1	Lane 2	Lane 3	Lane 4
02 ETD	900	900		
03 ETD	900	1200		
04 ETD	900	1200	2000	
05 ETD	1500	1500	2100	
07 ETD	1600	1600	1600	
08 ETD	1400	1800	1700	
10 ETD	1800	1500	1000	
11 ETD	1700	1700	1700	
12 ETD	1500	1700	1700	
13 ETD	1500	1700	1600	
16 ETD	1500	1600	1700	
17 ETD 01	1200	1200	1200	1200
17 ETD 02	900	1100		
18 ETD	1200	1200		
19 ETD	1400	1200	2100	1200
20 ETD	1500	1400	1500	1100
21 ETD	1500	1500	1700	1400
22 ETD	1500	1500	1500	900
23 ETD	1700	1500	1500	1300
25 ETD	1500	1500	1400	1200
26 ETD	1500	1500	1300	1300
27 ETD	1500	1700	1300	900
28 ETD	1400	1600	1300	200

These maximum flows are conditioned by low demand, capacities of upstream locations or even capacities of locations downstream relatively near (traffic light, ramps).

One observation in the fundamental diagrams is: when free flow speeds are greater, the occupancies where the diagrams change the tendency to congested state are lightly smaller.

BOTTLENECK DETECTION

We have detected the activation of 5 different bottlenecks. Figure 7 presents the situation of the bottlenecks throughout the highway. Three of them are diverge bottlenecks, one is a merge bottleneck and the other one is in the entrance of the city.

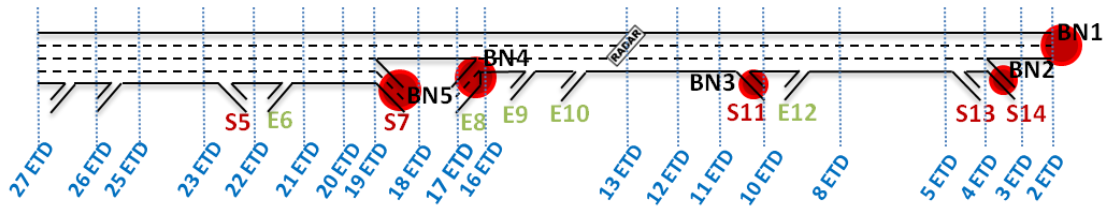


Figure 7: Bottlenecks situation map

In order to detect the bottleneck activation and deactivation with accuracy, we have used *Cassidy and Bertini* methodology which consists on comparing in the same diagram transformed cumulative count and transformed cumulative occupancy curves. When the curves reveal a flow reduction followed by an increase of occupancy, it means that a queue has arrived in that location. In the following cases this phenomenon is caused by the activation of a bottleneck downstream. Moreover, we define bottleneck capacity as the flow of all lanes while bottleneck remains active.

In addition, reducing cumulative curves by a background value (transformed curves) magnifies details.

Bottleneck 1

We found the first bottleneck in the entrance of the city. It would be caused by the traffic light that is located at the same entrance of the city. The bottleneck activation is detected by loop detector 02ETD, which is located 370 meters upstream the traffic light. This part of the highway has two lanes.

Figure 8a reveals the bottleneck activation that is produced around 7:36, where transformed cumulative count curve drops while transformed cumulative occupancy curve rises. Meanwhile, Figure 8b presents the bottleneck deactivation that is produced around 10:00, when both curves converge.

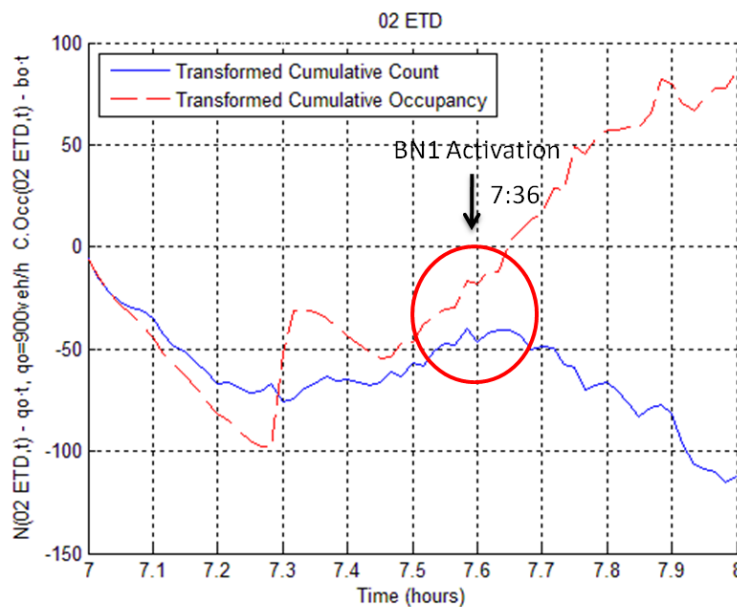


Figure 8a: Bottleneck 1 activation

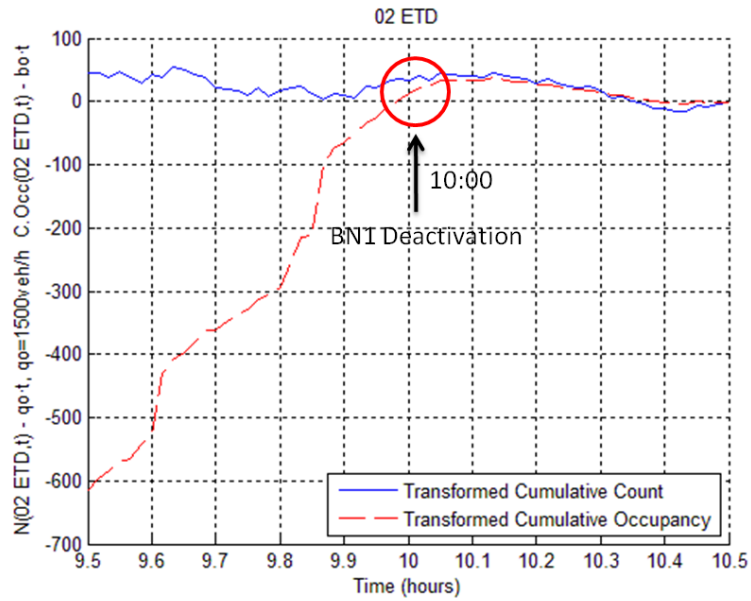


Figure 8b: Bottleneck 1 deactivation

The time when curves diverge/converge is the time when the queue (produced by the bottleneck) arrives/disappears at that loop detector. This time is the best approximation of the real activation/deactivation time that we can obtain with our data. That is why we will take it as a good approximation.

Figure 8c shows the variation flows around the time that bottleneck was active. We can observe that flow drops between 1880 veh/h and 1490 veh/h when bottleneck activates. Additionally, while the bottleneck is active there are two different behaviors (flows). They were probably caused by a change of the traffic light cycles or the spillover of vehicles from the urban area.

According to our analysis we can conclude that the capacity of bottleneck 1 is 1420 veh/h through the two lanes. This capacity is calculated as the average discharge rate while the bottleneck remains active.

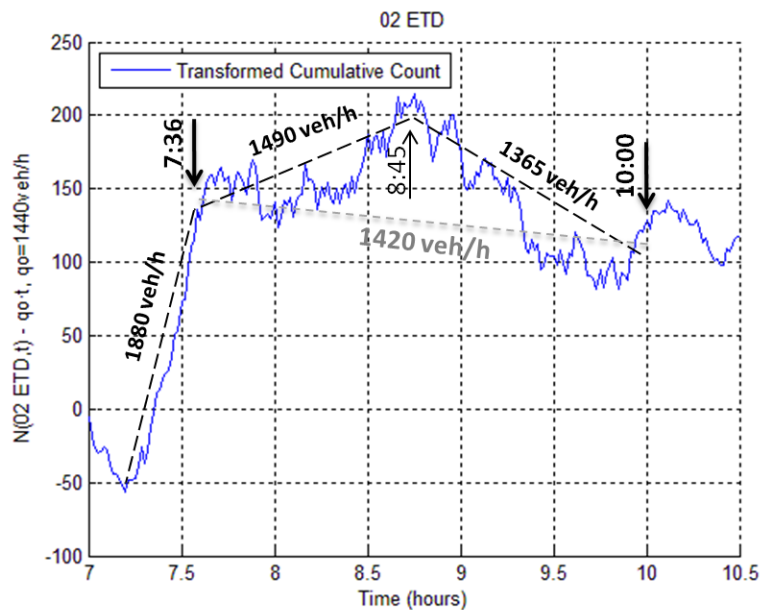


Figure 8c: Bottleneck 1 capacity and flow variations

Bottleneck 2

The second bottleneck is located in PK 0.99 (off ramp S14). The highway reduces one lane in the off ramp (3 lanes to 2 lanes). This diverged bottleneck is detected in loop detector 04 ETD, located 100 meters upstream from S14. The third lane is directly affected because it is the off ramp lane. That is why the third lane is the only one used to identify activation and deactivation times.

Figure 9a reveals the bottleneck activation time (7:17). Additionally, it shows the time that queue from bottleneck 1 arrives at that location through lane 1 and 2 (7:45). Figure 9b, on the other hand, shows deactivation time that occurs around 9:35.

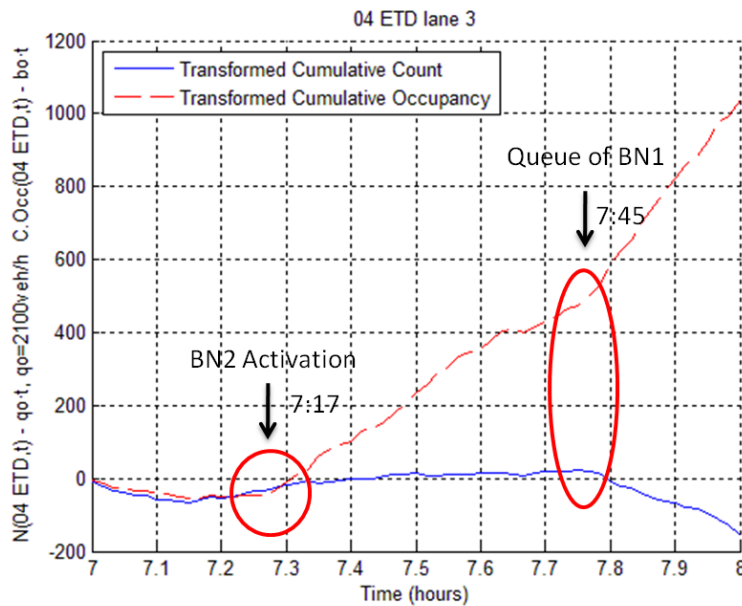


Figure 9a: Bottleneck 2 activation

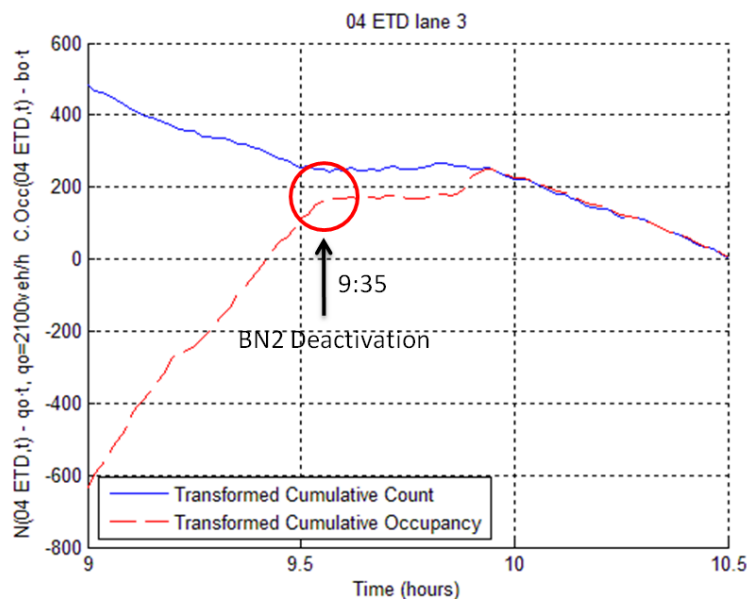


Figure 9b: Bottleneck 2 deactivation

Figure 9c displays the flow variations in all lanes while the bottleneck remains active. We can distinguish three different behaviors during this period. The first one is between the activation time and 7:45 and it has the

higher discharge rate (4600 veh/h). The following one is between the time when queue of BN1 arrives at BN2 (7:45) and 8:18 approximately, 4200 veh/h is the discharge rate during this period. The last and more critical period is between 8:18 and the deactivation time (9:35), with a discharge rate of only 3450 veh/h.

Around 8:18 a drastically flow reduction is observed. It could be caused by the reduction of the capacity of off ramp S14 that directly leads to a flow reduction of lane 3. This could be produced by a severe congestion of the beltway (Ronda de Dalt) where the off ramp leads into.

The capacity of bottleneck 2 is 3900 veh/h through the three lanes.

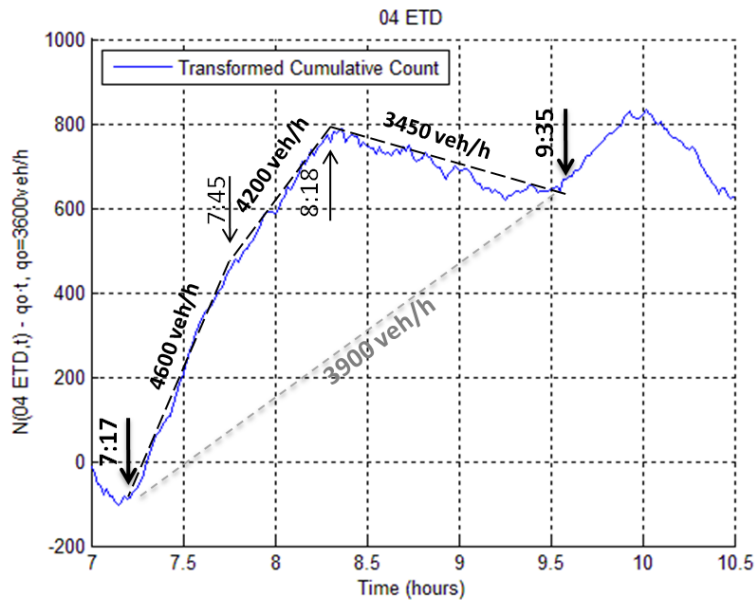


Figure 9c: Bottleneck 2 capacity and flow variations

Bottleneck 3

Bottleneck 3 is a diverge bottleneck and it is located in PK 3.57 (off ramp S11). Loop detector 11 ETD is used as a bottleneck detector. It is situated 220 meters upstream from the off ramp, after which the three lanes remain downstream. As we did in BN2, we used only lane 3 for activation and deactivation times.

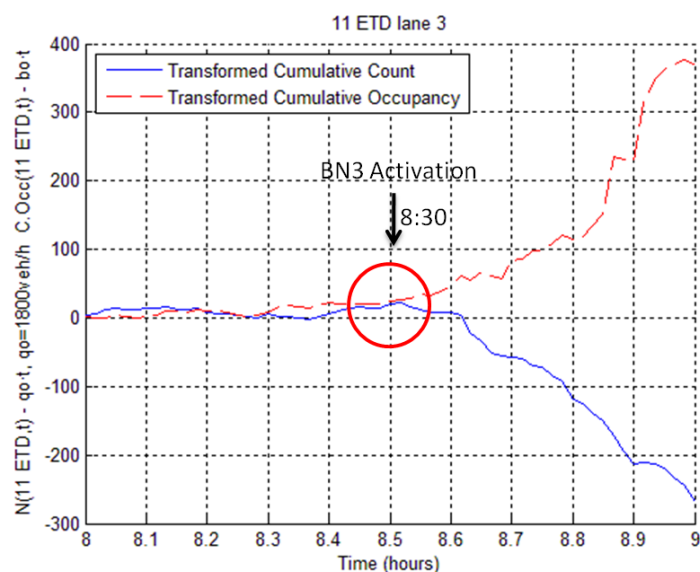


Figure 10a: Bottleneck 3 activation

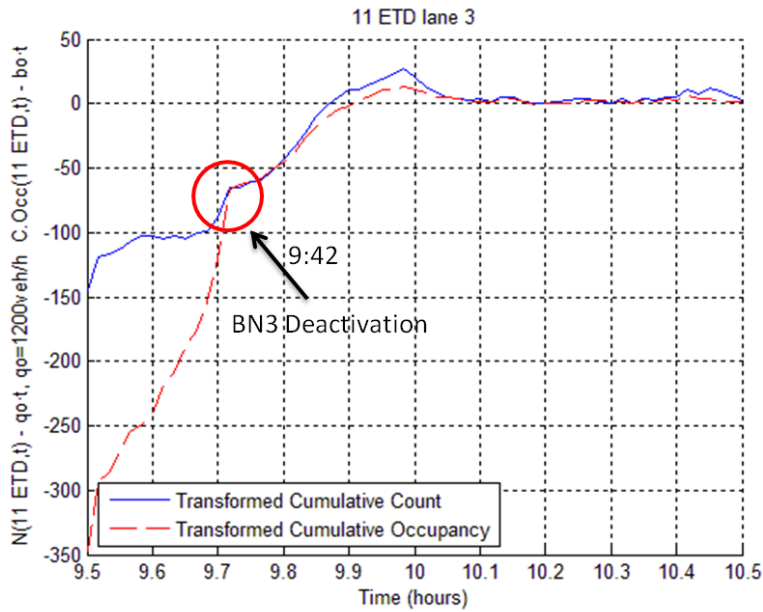


Figure 10b: Bottleneck 3 deactivation

Figure 10a shows the activation time of BN3 that happens around 8:30. Figure 10b, on the other hand, displays the deactivation time (9:42). The period of time while the bottleneck is active is 1 hour and 12 minutes. The capacity of bottleneck 3 is 4480 veh/h.

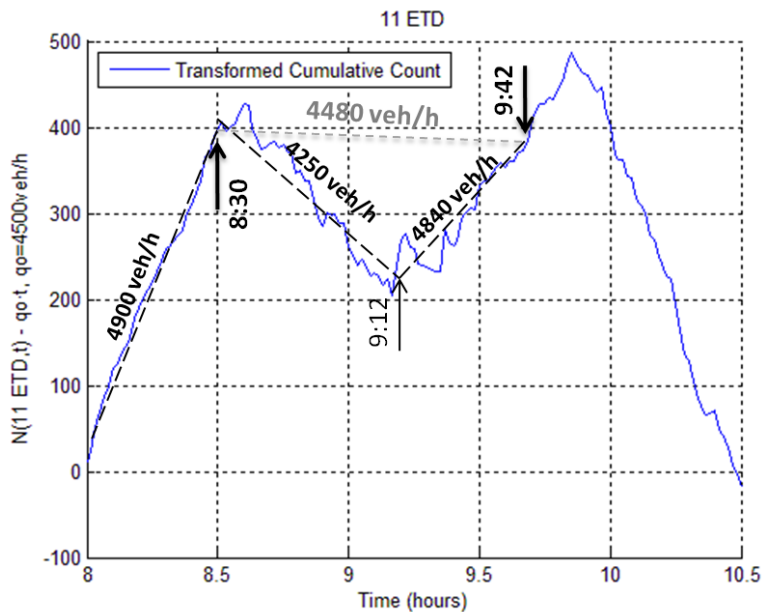


Figure 10c: Bottleneck 3 capacity and flow variations

Bottleneck 4

This merge bottleneck is produced by on ramp E8 and it is detected by loop detector 16 ETD, which is only 50 meters downstream. In this case, when the bottleneck activates, all lanes (3) are affected simultaneously. That is why we used the added data of the three lanes to identify activation and deactivation times.

Figure 11a reveals the activation time, which is produced around 7:35. Figure 11b shows the deactivation time of bottleneck 4 (8:18).

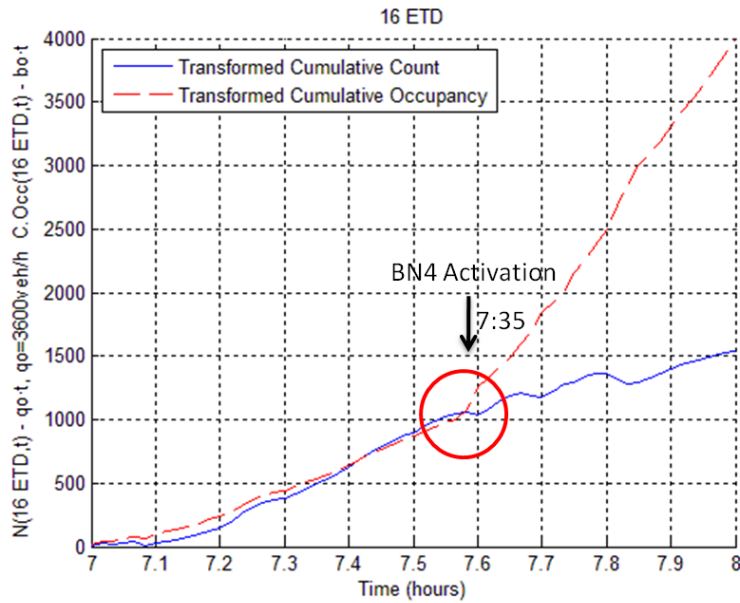


Figure 11a: Bottleneck 4 activation

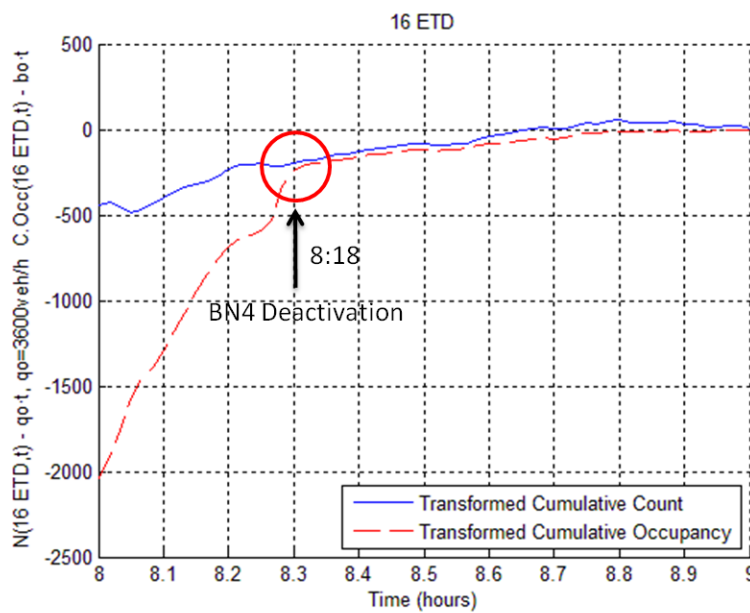


Figure 11b: Bottleneck 4 deactivation

This bottleneck is only active during 43 minutes, the shortest period of the 5 bottlenecks. The activation of the bottleneck produces 20% reduction in the discharge rate. The capacity of the bottleneck is 4650 veh/h through three lanes.

We observe that deactivation of BN4 is produced about 15 minutes after the activation of BN5. When BN5 activates, it reduces the discharge rate of the lanes in that location, this means that fewer vehicles arrive in downstream locations. If the demand is reduced in BN4, the bottleneck could be deactivated easily. We suggest that bottleneck 4 is related with bottleneck 5.

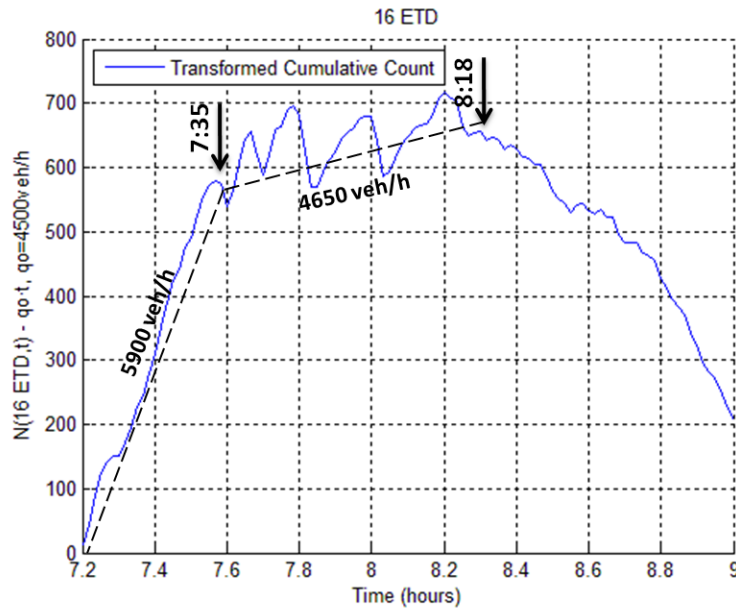


Figure 11c: Bottleneck 4 capacity and flow variations

Bottleneck 5

The last diverged bottleneck is located in PK 7.18 (off ramp S7). We used loop detector 19 ETD to detect this bottleneck. It is located 100 meters upstream S7. The off ramp leads out 2 lanes to another highway. In this location the lanes in the highway change from 4 to 2. In order to analyze the activation and deactivation time with accuracy, we used the two lanes of the off ramp together (lane 3 and 4).

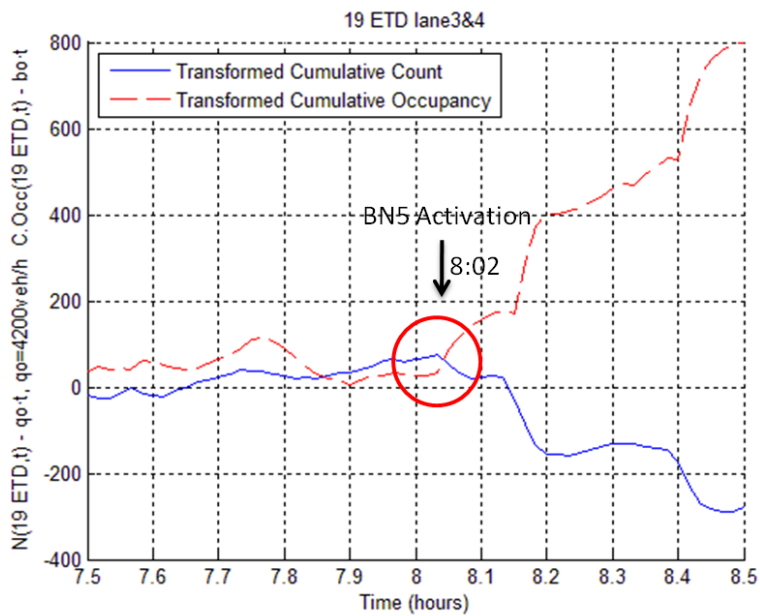


Figure 12a: Bottleneck 5 activation

Figure 12a shows the activation time of bottleneck 5, which is produced around 8:02. On the other hand, Figure 12b reveals the deactivation time (9:48).

Finally, Figure 12c presents the flow variation measured around bottleneck 5 in all the lanes (4). The discharge rate is reduced 30% when the bottleneck activates. The capacity of bottleneck 5 is 4930 veh/h.

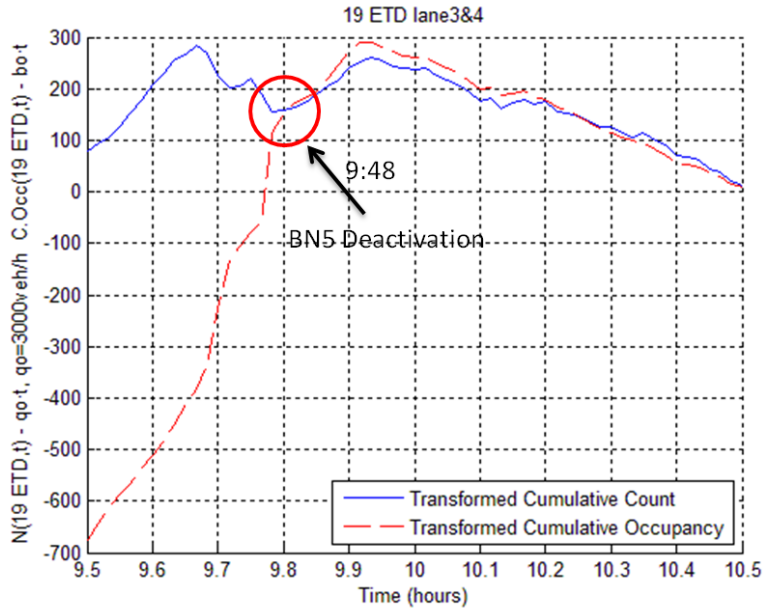


Figure 12b: Bottleneck 5 deactivation

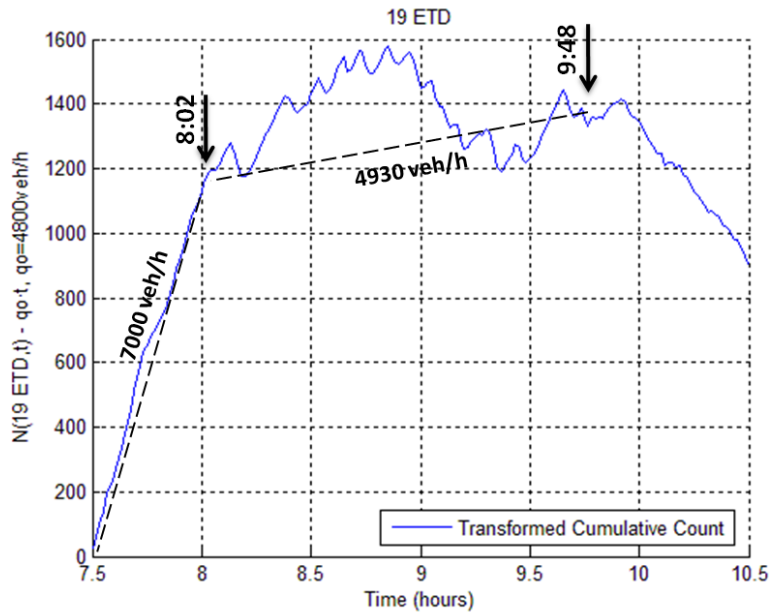


Figure 12c: Bottleneck 5 capacity and flow variations

	PK	Time activation	Time deactivation	Lanes	Bottleneck Capacity (veh/h)	Average BN Capacity per lane (veh/h)
BN 1	0,09	7:36	10:00	2	1420	710
BN 2	0,99	7:17	9:35	3	3900	1300
BN 3	3,57	8:30	9:42	3	4480	1493
BN 4	6,20	7:35	8:18	3	4650	1550
BN 5	7,18	8:02	9:48	4	4930	1233

Table 4: Resume of Bottleneck data

CONGESTED TRAFFIC ANALYSIS

The congestion appears in two different periods during the day, we analyzed them separately. The first and more important one is the morning congestion between 7:00 and 10:00. The second period of congestion appears in the afternoon between 17:00 and 20:00, mostly in the last 3KM near the entrance of Barcelona.

Congestion generally appears disaggregated through the lanes due to the weight of ramps in our section. Especially off ramps cause long queues at rush hours in the lane that access to it. That is why it is important to make the analysis with no aggregated data lane.

Congested state appears generally when occupancy reaches 15%. Thus, we usually consider the lane is congested if its occupancy is over 15%.

Moreover, we have used travel time index⁵ in order to measure the delays caused by congestion.

MORNING RUSH HOUR (07:00 -10:00)

During the rush hours and when congestion and queues have not been formed yet, the travel time index in the first part of the highway (between KP 11 and KP 7) is 1.1 - 1.3, i.e. drivers need around 10% and 30% more time to pass through that part of the highway due to the extra number of vehicles. While in the second part of the highway, the travel time index in the same period of time is 1.2 - 1.5.

Variable Speed Limits change usually between 7:30 and 10:00, also the same period as congestion appears.

Between 7:10 and 7:40 the two bottlenecks nearer the city are activated. This produces the formation of queues in the entrance of Barcelona.

The first bottleneck activates around 7:36, creating a queue that drops speeds down to 25-30km/h. The queue spillback in the two lanes and it reaches KP 0.74 at 7:45 and KP 1.1 at 8:00. VSL oscillates between 40 and 50km/h while bottleneck 1 is active (these speed limit variations are caused by the traffic light cycles). However, average speeds measured are under the speed limits. This congestion begins to disband at 9:15 in KP 1.1 and it finally disappears around 10:00 in the entrance of Barcelona. There are not significant flow drops but there are speed drops that are not caused by VSL. Additionally, the travel time index is around 2.5 and 3, i.e. drivers need 150-200% more time to pass through this congested area compared with no congested hours.

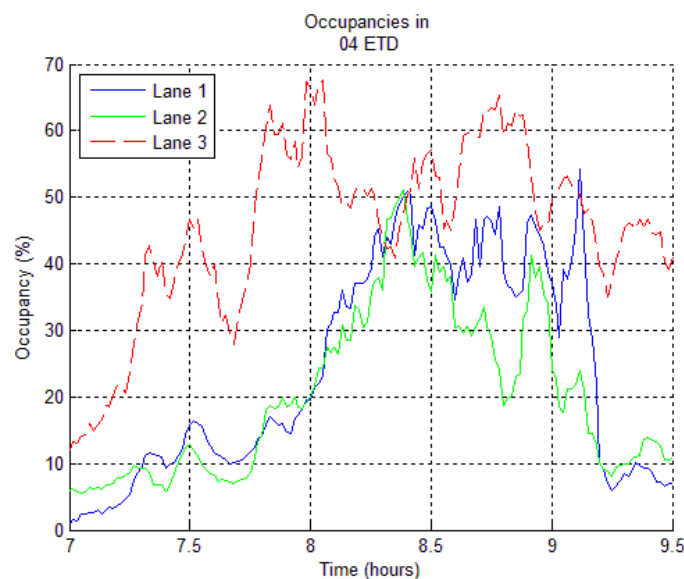


Figure 13: Occupancies measured in 04ETD

⁵ All the values of the travel time index during rush hours are shown in Annex C.

The second bottleneck is activated around 7:17 in the access of Barcelona Beltway (off ramp S14) congesting the third lane. The queue spills back 1.4Km very fast. In this lane the flow is higher compared with the first and second lanes, because the capacity of the off ramp is higher than the capacity of the traffic light situated in the entrance of the city (1 KM downstream). Moreover, Figure 13 shows that the queue formed in BN1 arrives (throughout two main lanes) at location of BN2 at 7:45 and disappears at 9:15. During 8:00 and 9:00 the flow drops significantly to 1400veh/h in the third lane while the discharge rate during the 45 minutes before was 2200veh/h. This abrupt change in the discharge rate of the off ramp could be explained by the congestion in the urban area near the ramp, which creates queues that spillback to the highway throughout the ramp. The bottleneck 2 deactivation is produced around 9:30.

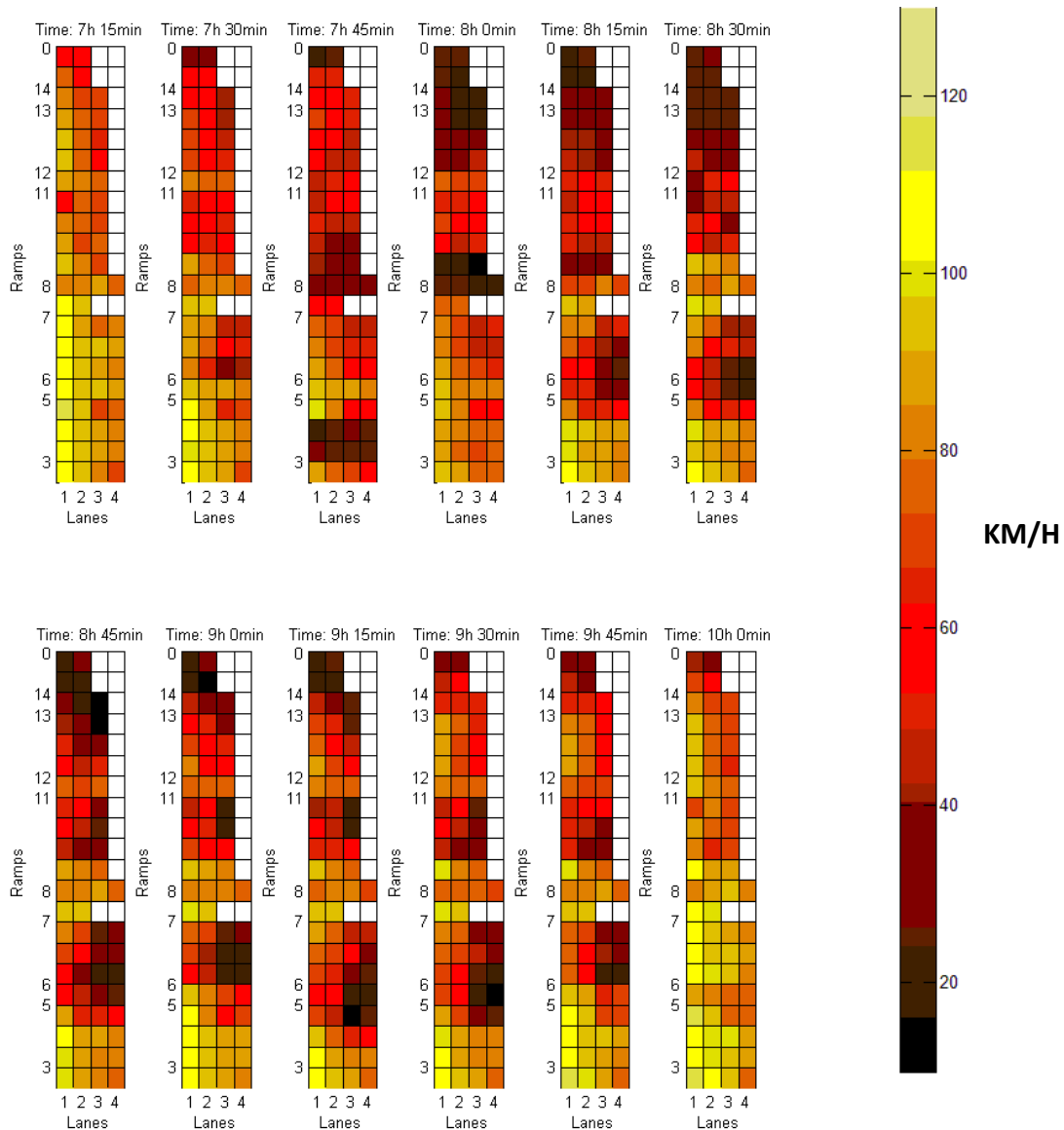


Figure 14: Congestion Evolution Diagram in the Morning Rush Hours with speed as the variable

Moreover, the off ramp S13 (located 370 meters upstream of S14) gets congested at the same time and between 8:30 and 9:15 the flow in the third lane near the ramp drops to 600veh/h. Speeds also drop between 15km/h and 20km/h. At 800 meters upstream, a flow drop 450veh/h is observed in the third lane between 8:45

and 9:15. This phenomenon could be caused by the spillback of the queue that comes from the congested urban area next off ramp S13 or merely for the low capacity of the ramp S13.

In the vicinity of the off ramp S11 between 7:30 and 8:30, some punctual congestions as drops of speed are observed. It precludes the activation of bottleneck 3 in this ramp, which is produced approximately at 8:30. At first, the queue is generated in the third lane and it affects gradually the other lanes. The queue of the third lane spills back 800 meters with drops of speed to 20Km/h, while in the other lanes vehicles flow at 50 km/h. During this period of time VSL varies between 50 and 70 km/h. Thus VSL does not affect the behavior of the third lane drivers but it could affect the behavior of the drivers of the rest of lanes.

A lot of vehicles access to the highway through on ramp E8 during morning rush hour. This produces the activation of bottleneck 4 around 7:35, which is located just in this ramp. The congestion in this bottleneck, unlike others, appears in all the lanes at the same time and it causes a drop of speeds to 15-35Km/h. Figure 15 shows the behavior of VSL, which follows the behavior of the drivers (It reduces speed limit 2-3 min after the traffic have reduced their speed). Figure 15 reveals as well the flow fluctuations. While the bottleneck is active the flow fluctuates between 1000veh/h and 1800veh/h per lane, this could be produced by stop and go traffic. This bottleneck produces a queue that spillbacks till 500-700 meters generating a drop of speeds to 50km/h in upwards locations. While travel time index takes values around 3 and 4, i.e. people need 2 and 3 times more time to pass through that area compared with no congested times. However, bottleneck remains active not much more than 40 minutes.

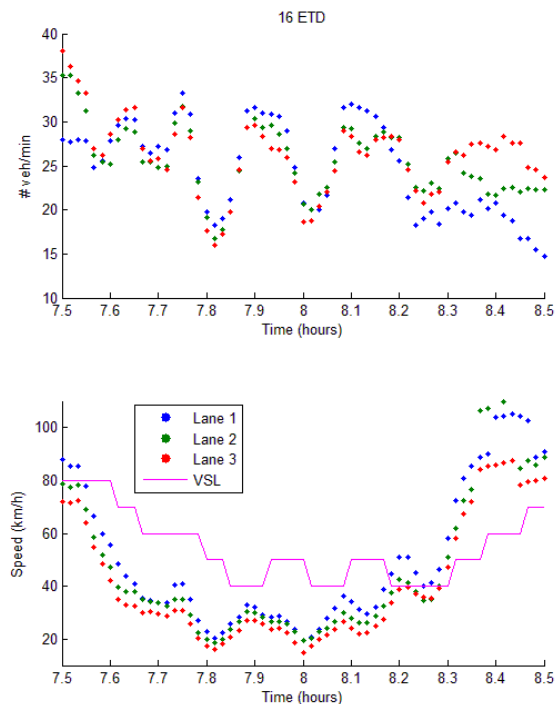


Figure 15: Flow and speeds measured in 16ETD

Off ramp S7 is the location of the last bottleneck (BN5). It activates around 8:00. The queues are generated in the third and fourth lane (lanes of the off ramp), where speeds drops to 30km/h. However, the VSL in these two last lanes enforce speeds between 50km/h and 60km/h. This behavior propagates till 1km upstream decreasing gradually the difference between lanes, and only between 9:00 and 9:30 the queue reaches 2km upstream affecting mostly the two slowest lanes. Lane one and two are less affected by congestion in this area. The travel time index in this highway area is very different between the two fast lanes (travel time index is

around 1.3, drivers need only 30% more time) and the two slow lanes (third and fourth lanes) where it takes values around 2 and 3, i.e. drivers need 100%-200% more time to pass through this area during congestion.

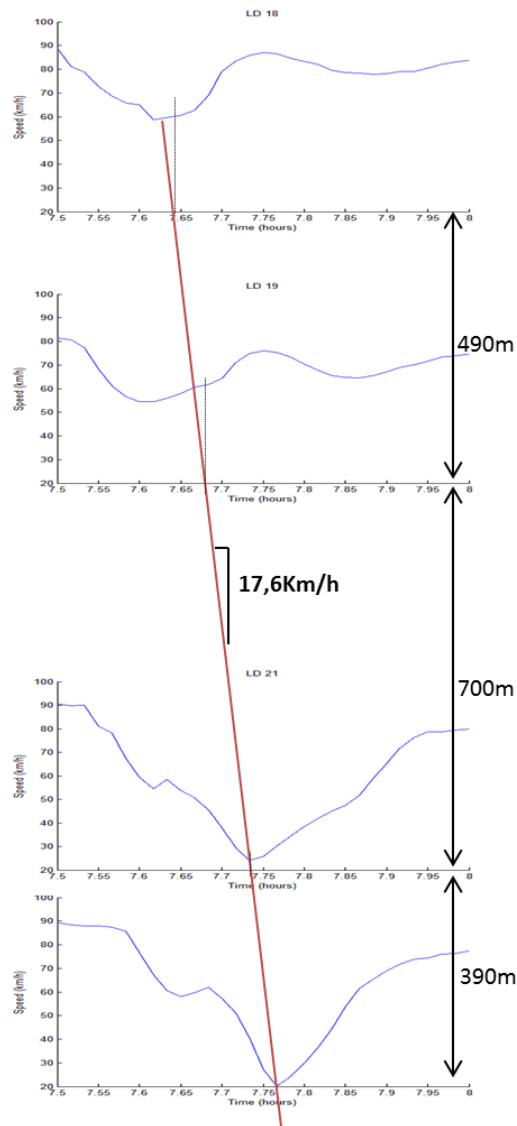


Figure 16: Traffic Oscillation

Around 7:45, in the proximities of KP 9.5, one traffic oscillation became the trigger that started a punctual queue that affected all the lanes and it spillbacks 1.5km but it disappeared quickly. It produced a drop of speeds to 20km/h in the first 800 meters upstream and a speed drop to 40km/h beyond. This traffic oscillation can be seen in Figure 16 and it spillbacks with an average speed of 17.6Km/h.

AFTERNOON RUSH HOUR (17:30 -20:00)

In the afternoon rush hour, the congestion only appears at the second part of the highway, i.e. between KP 6 and the entrance of Barcelona. In the first part of the highway, higher flows are observed but no congestion appears. The reason for this phenomenon could be that the highway in the first part has one lane more than in the second part. We will only analyze the area where congestion occurs.

The VSL only acts in the second part of the highway and mostly between 18:00 and 20:00. The congestion begins and evolves very similar as it does in the morning rush hour.

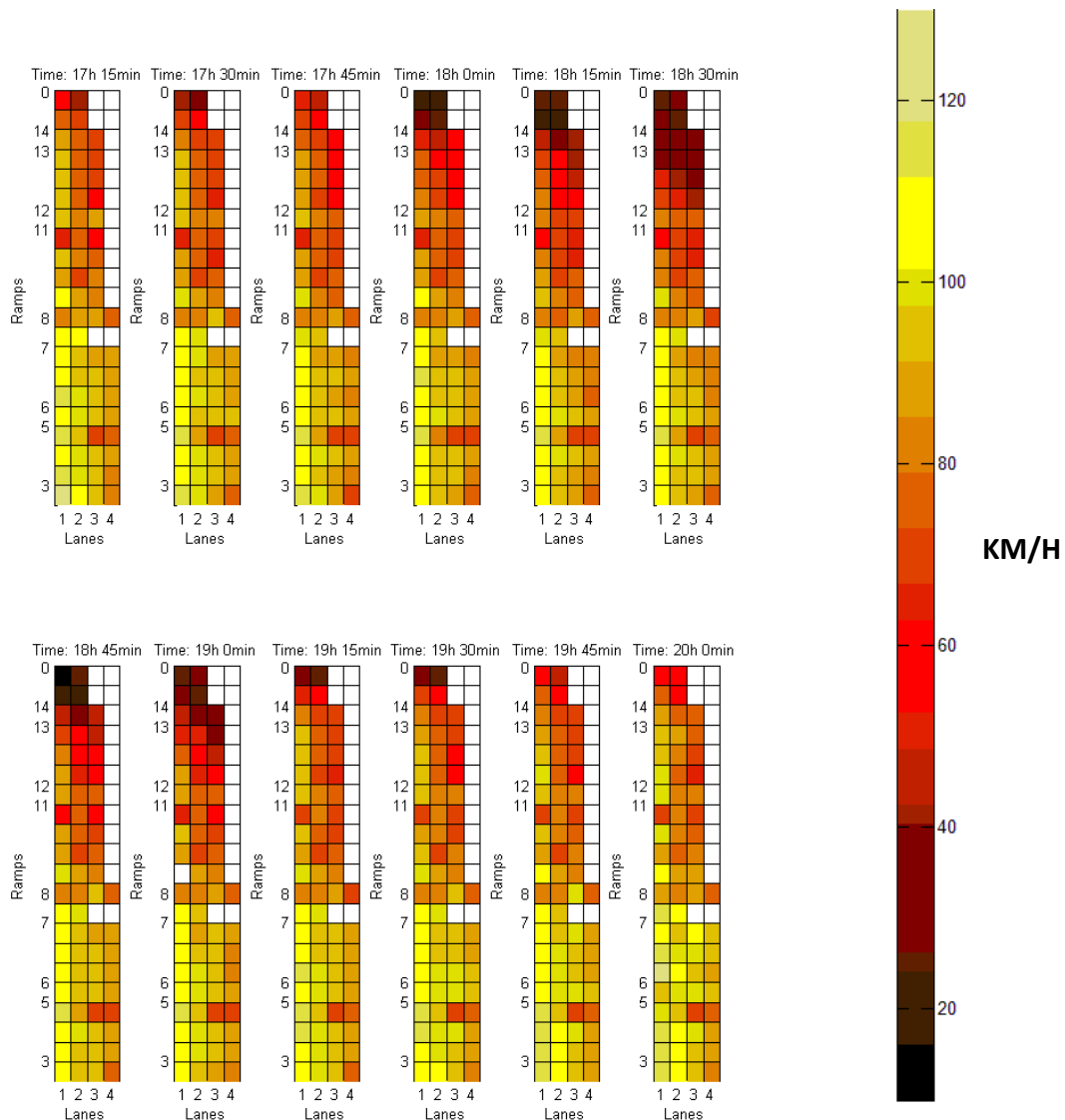


Figure 17: Congestion Evolution Diagram in the Afternoon Rush Hours with speeds as the variable

During the afternoon rush hour only the first two bottlenecks activate. The first one activates around 17:50, it drops the speeds to 20-30km/h. The queue spillbacks slowly (0.5Km/h) reaching KP 0.74 at 17:54, KP 1.1 at 18:03 and KP 1.51 at 18:24. Near the entrance of the city the VSL varies between 40-50 km/h and the measured occupancies also vary a lot due to the cycles of the traffic light. 400 meters upstream we can observe very high occupancies in both lanes and the VSL fixed in 40km/h between 17:55 and 19:10. A drop of flow of 40% in lane 2 is also observed in this location due to congestion. The queue completely disbands at 19:06 in KP 1.1 and at 19:45 in the entrance of the city. During the period that the congestion appears the travel time indexes moves between 2 and 3.

The second bottleneck also activates around 17:50. The queue formed in BN1 arrives at location of BN2 15 minutes after it is created. Near off ramp S13 congestion appears around 18:30 affecting all the lanes and dropping speeds to 30km/h. Moreover, around 19:00 congestion appears in the third lane dropping their speed to 35km/h and also reducing flow by 20%. VSL signal drops the speed limit in this location to 50 between 18:00 and 19:00 except 10 minutes after 18:30 that it drops to 40km/h.

In the proximities of KP 3.5 (off ramp S11) no congestion is appreciated, but the speeds are 5-10% slower between 18h and 19h compared with free flow speeds. This period matches when VSL drops to 60km/h and 70km/h the speed limit in this area. This decrease of the measured speed may be caused by the VSL, which at the same time could not allow the congestion to appear.

The area situated upstream PK 4 is not affected by the rush hour.

We can conclude that the congestion is generally caused by the low capacity of the off ramps and the low capacity of the entrance of the city due to the traffic light. We have also seen that afternoon congestion is not very important. Additionally, when congestion occurs people need between 1 and 3 times more time to pass through the same area compared with uncongested times.

CONCLUSIONS

The analysis of the variable speed limit strategies in a European highway has been presented in this thesis. The measured data used for the thesis is from a highway of Barcelona and it only uses the data of a single day. Different tools as fundamental diagrams, transformed cumulative curves, contour plots are used for the study and analysis of the data.

One goal of this thesis was the bottleneck detection and diagnostic. Through transformed cumulative curves of vehicle counts and occupancies 5 different bottlenecks are detected. Three of these bottlenecks are diverge bottlenecks, one merge bottleneck and the last one a traffic light bottleneck in the entrance of the city. This means off ramps creates most of the congestion in the highway. Diverge bottlenecks usually are generated for low capacity of the ramps.

The analysis reveals that occupancies just before off ramps in diverge lanes are highest than in locations not near them. This causes a lot of lane changes in the last meters before the ramps. The same occurs after the off ramp. These changes occur because the average speed between lanes is very different. However, one of the purposes of VSL is harmonize the speed within lanes and as we can see in the thesis it is not functioning as it should be.

Another interesting observation regarding occupancies is that the risen of the occupancy is more important in lane 1 than in the other lanes when the highway becomes more demanded. In uncongested states, occupancy in lane 1 is the lowest. However, when demand increases the occupancy in lane 1 rises until all the lanes have more or less the same occupancy.

It is also seen from the study that VSL are not obeyed for most of the drivers. The measured speeds show that people that drive in the first lane (fastest) usually do not respect speed limits. However, second lane drivers obey it more often. This could be explained by the infrastructure, which is designed for higher speeds and drivers could not see a reasonable reason for not speeding. Moreover, in congested periods, variable speed limits are above the measured speeds and VSL changes the speed 3-5 minutes after the traffic has changed its behavior. VSL does not have any effect in traffic behavior once congestion has occurred.

We suggest trying to change the control algorithm of the actual VSL for one that acts on time and affects in congestion situations either upstream locations (reducing speeds) or downstream locations (could increase the speeds to allow more discharge rate).

One possible solution in the case of merge bottlenecks could be the ramp metering. In our highway we have only one merge bottleneck and the introduction of this traffic strategy would be an issue to study.

The direction for further studies goes towards studies with a bigger range of data, in order to be able to compare data of various days and see the traffic constraints that are repeated. If it is possible, it would be interesting to obtain data of more congested situations, since VSL acts in congested states.

We will give some problems that need to be fixed or recommendations for future studies in this highway (B23):

- Vehicle counts through the ramps (either off ramps or on ramps).
- Check the correct operating of some loop detectors that had give us some data problems:
 - o Speeds Measure of 11 ETD lane 1
 - o Speeds Measure of 23 ETD lane 3 and 4
 - o The complete measurements of 24 ETD lane 3
 - o Vehicle counts of 19 ETD lane 3 seems to be over measured

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