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Títol

**Freeway Traffic Experiment – Empirical Traffic Data
Under Dynamic Speed Limit Strategies**

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ABSTRACT

The goal of the present Master Thesis is the development of a field experiment at the B-23 freeway accessing the city of Barcelona. The work aims to be a future reference for researchers, as it provides a unique database and also some guidelines for designing similar experiments. All the relevant issues faced during the experiment are explained in detail making the reader aware of the main difficulties.

The experiment intends to provide enough quality data to definitely answer how the DSL affects traffic in a real freeway. Some of its supposed benefits are an increase of the maximum capacity and travel time reduction in congested periods and less air pollution. These possible benefits are still subject of intense scientific debate. The main reason for that is the lack of adequate data in order to prove or discard these assumptions. The present work is a first step towards achieving this goal.

Video analysis is subject to a specific focus. Video tape recordings are the source measurement for obtaining lane changing data. Lane changes play a fundamental role in freeway traffic efficiency. In spite of this, lane changing data is scarce due the difficulties in their measurement and extraction from video. Video analysis and lane changing extraction in experiment sites is usually done manually. The time required in this process is huge, as it implies actually looking the whole video length several times. Some alternatives are considered here, ranging from a fully automatic data extraction via software, to a total manual data extraction via watching the full video length. A compromise solution is reached. An ad-hoc semi-automatic software is designed. This allows using the regular video recordings available at many traffic management centers (that fully automatic treatments do not allow) but still reducing to approximately a 10% the amount of men-hours needed in order to extract the lane changes from the video. A test application to the experiment site is presented.

Furthermore, some data quality analysis is done to ensure the data from freeway sensors are reliable. This is presented to the reader by means of contour plots and time series. This preliminary data analysis allows drawing some conclusions about the fulfillment and effectiveness of the DSL system in this freeway. It is concluded that dynamic speed limits are only fulfilled by most of the drivers on sections with enforcement devices (i.e. radars). Otherwise speeding is generalized. This result should guide traffic administrations in the selection of locations candidates for speed limit enforcement. In addition, it is proved that the lane changing activity increases with the occupancy of the freeway. This means that, when congestion appears, flow is reduced, but lane changes continue growing. Lane changing in congested conditions is detrimental for traffic efficiency, and active management strategies should be designed in order to address this situation.

RESUM

L'objectiu d'aquesta tesina de final de carrera es el desenvolupament d'un experiment sobre l'autopista B-23 d'accés a la ciutat de Barcelona. Aquest espera ser una futura referencia per a investigadors, ja que proporciona una base de dades única a més d'algunes línies directrius per al disseny d'experiments similars. Tots els problemes rellevants succeïts en l'experiment s'expliquen detalladament per a que el lector en sigui conscient.

L'experiment vol proporcionar dades de qualitat per respondre definitivament com els límits de velocitat variables afecten al transit en una autopista real. Alguns dels seus suposats beneficis son l'increment de la capacitat màxima i una reducció del temps de trajecte durant els períodes congestionats; també una reducció de la contaminació atmosfèrica. Aquests possibles beneficis estan encara immersos en un intens debat científic. La principal raó de que això succeeixi es la manca de dades adequades per a provar o descartar aquets supòsits. Aquest treball és un primer pas cap a l'assoliment d'aquest objectiu.

L'anàlisi de vídeo es objecte d'especial atenció, les gravacions de vídeo son la font de la qual s'obtenen les dades de canvi de carril. Aquests juguen un paper fonamental en l'eficiència del transit en una autopista. A pesar d'això, les dades de canvi de carril son escasses degut a les dificultats que presenta mesurar-les i extreure-les de les gravacions de vídeo. Habitualment en els experiments aquest procés es fa de forma manual, necessitant així una quantitat de temps enorme, ja que implica visualitzar tot el vídeo sencer varies vegades. Però hi ha alternatives, des de software de processat de vídeo totalment automàtic, fins a una extracció completament manual visualitzant el vídeo sencer. Finalment es va dissenyar un programari semi automàtic ad-hoc que permet usar les gravacions de vídeo disponibles a diversos centres de control de trànsit (que els tractaments completament automàtics no permeten), però tot i així reduint el total d'hores de feina a un 10 %. Es mostra l'aplicació per a l'experiment.

Adicionalment, s'ha realitzat un anàlisi de qualitat de dades, per tal d'assegurar que els sensors han proporcionat dades fiables. Aquest es presenta al lector per mitjà de "contour plots" i de sèries temporals. L'anàlisi preliminar de les dades permet extreure algunes conclusions sobre el compliment i l'eficàcia del sistema DSL a l'autopista. Es conclou que els límits de velocitat variables només son complerts per la majoria dels conductors en aquelles seccions amb els radars. En cas contrari l'excés de velocitat es generalitzat. Aquest resultat ha de guiar a les administracions s de trànsit en la selecció de les ubicacions per a als controls de la velocitat màxima. A més, es demostra que el nombre de canvis de carril s'incrementa amb l'ocupació de l'autopista. Això vol dir que, quan es produeix congestió, es redueix el flux, però els canvis de carril segueixen creixent. En condicions de congestió els canvis de carril són perjudicials per a l'eficiència del trànsit, i les estratègies de gestió activa han de ser dissenyades amb la finalitat de fer front a aquesta situació.

ACKNOWLEDGEMENTS

Only after finishing and submitting the present Master thesis, is when I can look back and clearly see all the hours spent: from the ones resulting from an inspirational moment that allowed overcoming what previously seemed impossible to do, to the resulting work coming from hours of patience and perseverance. This has allowed not only the development of this document but also the long process with the data before that has allowed to reach this point.

Along this long way lots of people accompanied me, so much that it is impossible to acknowledge all of them, but at least I would like to highlight a few of them. First of all, my family, and especially my parents that even though they not always agreed about the path I was following, have always given their support to me. Also, I want to thank in a very special way the support from Laura and Josep every time I faced some difficulties. They did everything that has been in their hands to help and encourage me.

I could not miss to thank Francesc Soriguera to let me do this work with him. Certainly it has been a big pleasure having someone with his knowledge and thoroughness supervising it. Also, Josep Maria Torné in particular and CENIT in general, who from their experience gave me some advice about data treatment and storage that for sure saved me a lot of headaches.

Acknowledge the collaboration of the *Servei Català de Trànsit*, as without them the entire data collection would have been impossible. Especially to those who were in the TMC during the experiment and the members of the *UTE acc. ACIS-sur Aluvisa* directed by Carles Argüelles and Javi Romero who had an extra work recording all the data.

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1 INTRODUCTION

Traffic congestion in big metropolitan areas is a huge problem in terms of time, money and pollution. Since improving the actual infrastructures with more lanes or building new ones is very expensive, some freeway traffic control strategies were tried in order to reduce traffic congestion. The most common ones are ramp metering and DSL.

DSL strategies are commonly used in European and American metropolitan freeways. In Barcelona (Spain) almost nothing had been done in terms of active traffic control until July 2007 when a 73-measure plan to improve air quality was introduced. One of its items was reducing the speed limits from up to 120 Km/h to 80 Km/h. Nevertheless, the final goal was to set up a DSL system. The first DSL corridor became operational in January 2009 as a test one. Later, in January 2012 it became operational on the B-23 freeway and, since then, the expansion through all freeways accessing Barcelona is being really fast. It is estimated that by the end of 2014 it will be completed in all the freeway stretches closest to the city.

In spite of its expansion and international popularity, the effects of DSL strategies are still not well-known. The usual claimed benefits imply reductions in pollutant emissions [5-7] and accident rates [8-90], as well as congestion relief [10-12]. It is claimed that these benefits are the result of the homogenization of traffic flow, which allows for increased capacity. However, these assertions are based on very scarce (or even inexistent) real empirical data. This means that these postulates should be taken as an intuition or a possibility more than as a scientific proven fact. Works analyzing real traffic data under DSL strategies exist [7, 13-15]. Some of these, [7, 14], consider the benefits of DSL strategies much more dubious in relation to those predicted by theory or simulation. Others report more promising results [13, 15]. All of them, however, base their results in aggregated traffic data on a test corridor under a specific DSL algorithm. This means that the results obtained are valid in order to test the aggregated corridor performance of a specific DSL algorithm, and therefore are highly site and algorithm specific. Conclusions on the the detailed drivers' behavior when facing different speed limits on the same infrastructure cannot be considered conclusive. The reason for this gap in the literature is the difficulty in measuring suitable traffic data. This difficulty has diverted research efforts to find optimal control algorithms [16-19] assuming some (unproven and inconclusive) effect of the speed limits on the traffic stream.

So with the aim to provide data that is the less corridor and algorithm specific to improve general knowledge about DSL for Barcelona freeways and all other ones over the world, an experiment was planned and done in one freeway accessing Barcelona, the B-23, see Figure 1.

2 SITE DESCRIPTION AND LAYOUT CONSTRUCTION

At the moment that this experiment was being planned there were only two corridors with DSL, the C-32 and B-23 freeways. The traffic administration in charge of both freeways, SCT (*Servei Català de Trànsit*), had to agree to the experiment. After some negotiations, they agreed about doing this experiment in the B-23 freeway. This is one of the main freeways accessing Barcelona. It is to the north-west of the city, providing access through the Llobregat river valley. See Figure 1.

Once the experiment site was chosen, a properly layout with all the geometric characteristics and all the equipment installed at the freeway had to be build. This information was provided for the SCT and contrasted from both, Google Earth and Google Street View.

The layout consists in three different parts:

- A schema (.pdf and .dwg) with a brief of all the elements, the schema is not in scale. See Figure 4.
- An Excel spreadsheet (.xlsx) with all the information available for each element. See Figure 2.
- A Google Earth file (.kmz) with all that in the previous parts, placed properly on the freeway. See Figure 3.

The freeway characteristics between Molins de Rei (KP 11.5) and Barcelona Diagonal Avenue (KP 0.00) are, as seen in the Figure 4; the freeway has 4 lanes in the first stretch, 2 lanes in a short connection distance between the A-2 freeway and the coast Barcelona beltway. And, finally it has 3 lanes in the second stretch connecting to the mountain beltway and the Diagonal Avenue at Barcelona city. It also has 9 on-ramps and 6 off-ramps.



FIGURE 1 Experiment site layout on the B-23 freeway. Obtained from © OpenstreetMap contributors, CC BY-SA.

The spreadsheet contains detailed information of every single element that appears in the schema shown. All the information available is in this file. A screenshot of this file is shown in figure 2.

The layout spreadsheet file is mostly self-explanatory. Only note that the entire technical names that could seem quite confusing were the ones used by SCT. So the decision was not to change them thus not to do double nomenclature which could be even more confusing. Moreover, all the geometric information was collected from Google Earth.

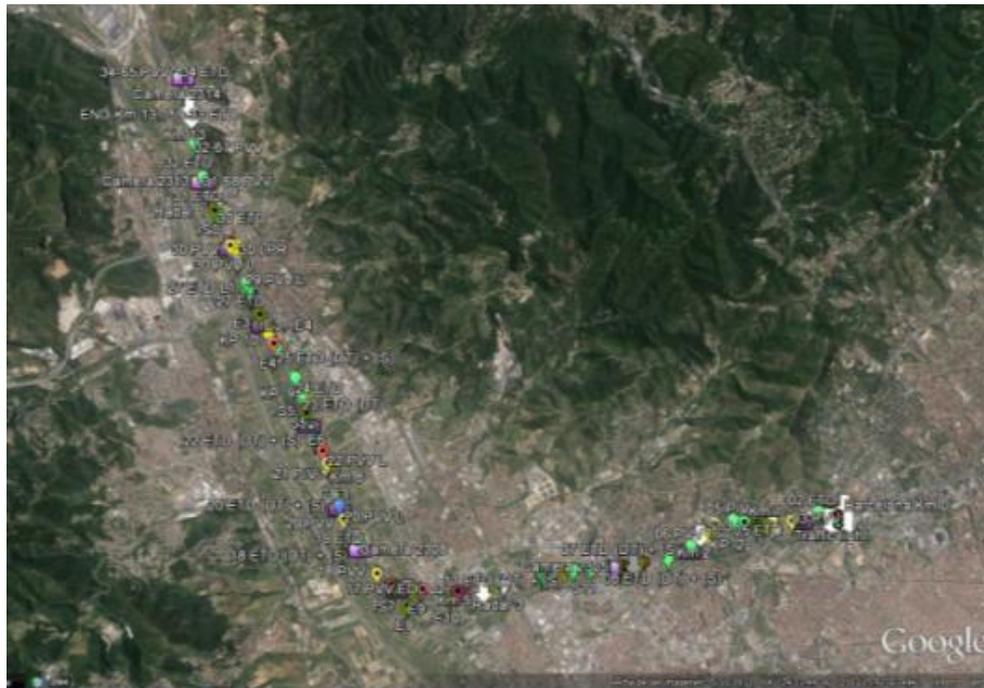
The construction of the schema and the excel Sheet that contains more information for each single element was a tedious work. Because of both, the need to be specific and unequivocal, and the fact that some of the information about KP delivered from SCT was outdated.

TABLE 1 Surveillance equipment installed on the experiment site

Equipment description			Number of units
Traffic Detectors	Inductive loop detectors (embedded in the pavement)	Double – ETD	11
		Simple – ETD(S)	12
	Non-intrusive detectors (on gantries – 3 redundant detection technologies: Doppler radar, ultrasound and passive infrared detection) named DT at present work.		13
Speed enforcement radar			2
TV cameras			11
License plate recognition devices			2
Dynamic speed limit signs (mainline – on gantries)			17
Dynamic speed limit signs (on ramps – on side panels)			5
Variable message signs			3

B - 23		Main Trunk						On / Off Ramps					
Element	Kilometric Post (KP)	Alias (Code used by the Traffic Management Center - SCT)	Max. Speed Limit (km/h)	# lanes	Shoulder width [m]	Lane Width [m]	# Lanes	Lane Width [m]	Shoulder width [m]	Length Auxiliar Lane [m]	Ramp Length [m]	Description	Comments
34 ETD	13.55			4	3.5	3.75							
38-65 PivV	13.55		120	4	3.5	3.75							
END Km 13.13	13.13			4	2.7	3.75							
31 ETD	13.15			4	2.7	3.75							
33-68 PivV	13.15		120	4	2.7	3.75							
32 ETD	12.62			4	2.5	3.75							
32-67 PivV	12.62		100	4	2.5	3.75							
31 ETD	12.17			4	3	3.75							Not working
32-68 PivV	12.17		100	4	3	3.75							Not working
Camera 2313	12.15			4	3	3.75							
S.D	11.88			4			3.75	3		280	250		
30 ETD	11.64			4	3	3.75							
32 PivV	11.64	B23-32-PVV-SD-01/02/03/04	100	4	3	3.75							
Radar 1	11.64	C129		4	3	3.75							Measures the 2 fastest lanes
S 1	11.25			4	3	3.75	1	4	4	(New Lane)	250		
CC 1	11.25			4	3	3.75							
28 ETD(S)	11.2	28 ETD 01 823 (simple)		3 (4)	4	3.5							3 lanes in main trunk + 1 auxiliary exit lane. S1 off-ramp.
30 PivV	11.2	B23-30-PVV-SD-01/02/03/04	100	3 (4)	4	3.5							3 lanes in main trunk + 1 auxiliary exit lane. Shows de DSL at the 3 main trunk lanes S1 off-ramp.
30 PivV L		B23-30-PVV-ED	80	1	4	3.5							Shows the DSL at the auxiliary lane S1 off-ramp.
30 LPR	11.2			3 (4)	4	3.5							3 lanes in main trunk + 1 auxiliary exit lane. S1 off-ramp.
Camera 2312	11.2	2312		3 (4)	4	3.5							Only measures the two fastest lanes. 3 lanes in main trunk + 1 auxiliary exit lane. S1 off-ramp.

FIGURE 2 Screenshot of the file Table_B23_inbound.xlsx .



a)



b)

FIGURE 3 Screenshots of Google Earth B23_inbound.kmz layout file. *a) General view of the entire study site. b) Detailed area between KP 4 and KP 3.*

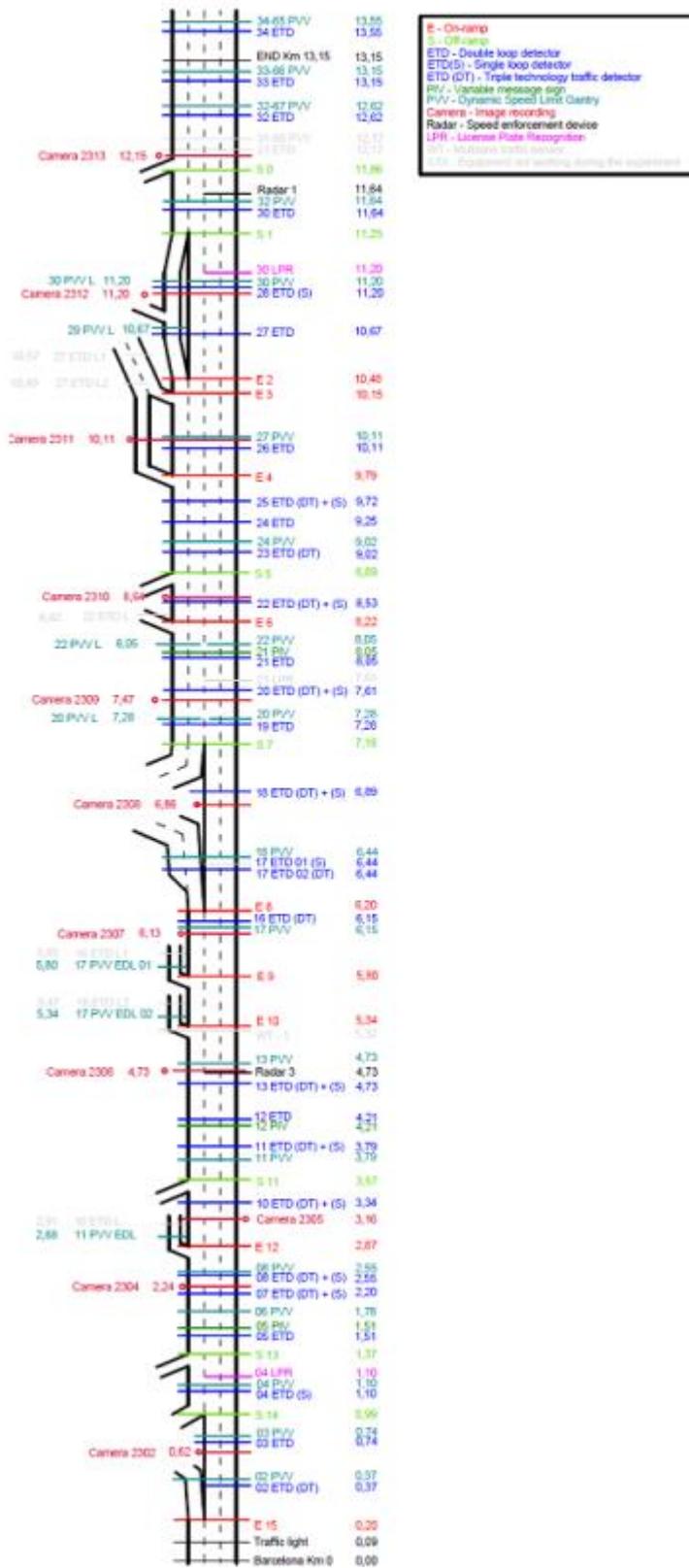


FIGURE 4 Experiment site layout diagram.

3 VIDEO PROCESSING

3.1 INTRODUCTION TO THE VIDEO ANALYSIS

The information given by the different freeway sensors, such as loop detectors and License Plate Recognition, is very valuable, but still incomplete. For research purposes, the more that is known, the better, so always is wanted to know as much as possible. In the case of traffic analysis, this is the space-time diagram for every single vehicle inside the study area. Obtaining such a complete information is very complicated, but some researchers have developed some software with the aim of supplying all, or at least part, of this information.

However, obtaining such complete information from video recording is impossible due to the high amount of time needed. In addition, even a simple lane change count, or car count using video recordings is extremely time-consuming, so all effort in this section will be dedicated to using the software that makes this task much faster.

The starting point was the information that most experienced people had about video process in terms of traffic analysis. There were different options: some were almost automatic, others some sort of fast manual. These ranged from the most fully-automated that gave the maximum amount of information to the most manual. The challenge was to obtain as much information as possible from the video data with the limited resources available, but the unavoidable goal was to have the lane changing data in the camera coverage area.

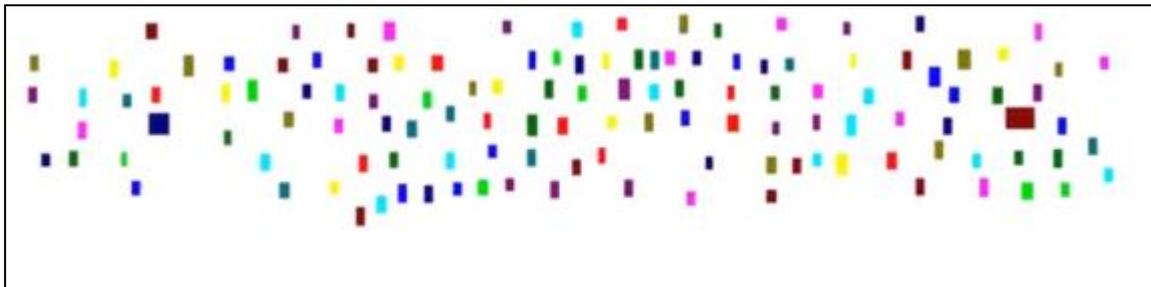
3.2 NGSIM SOFTWARE TOOL

The most automatic tool, so the first one attempted to use was NGSIM software. It is a very powerful program developed by Cambridge Systematics, Inc. for the Federal Highway Administration of the US government. This software, called NGSIM (Next Generation SIMulator), is able to automatically detect every single vehicle in the study area, and follow it through. Furthermore, it detects the size of each vehicle, so, at the end, the traffic behavior is known in great detail. It is such a powerful tool that extra information such as that supplied by loop detectors is no longer needed.

However, obtaining all this information has a big cost. The cameras have to be specially prepared, and some very specific software has to be used to create the input for the NGSIM analysis. Before the experiment, a trial run of NGSIM was carried out, with the aim of checking if the team was able to run this software properly. The process is described in detail below.



a)



b)

FIGURE 5 Example of NGSIM implemented on a freeway. a) Stretch of I-80 near San Francisco, CA, where NGSIM was implemented. b) Screenshot of the following video <http://www.youtube.com/watch?v=JjxNu2kbtDI>, which shows the data from the experiment that took place on the I-80 near San Francisco, CA. Each rectangle represents one vehicle on the freeway.

3.2.1 Camera Calibration

First of all, camera calibration is needed, because it is known that camera lenses distort the images, especially at the edges. This distortion depends on the lenses, the level of zoom and some other minor factors. This fact can lead a car which is travelling at a constant speed, to look like it is going faster when it appears at the edge of the image rather than at the center, or vice versa. See Figure 6.

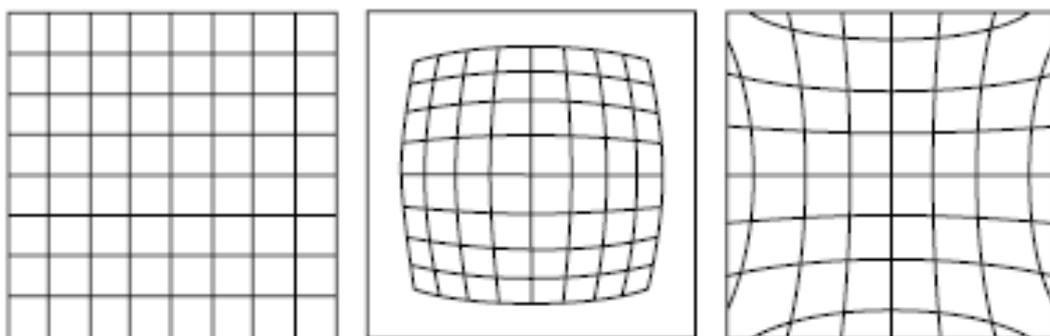


FIGURE 6 Typical distortion patterns. Left non distorted image. Center and right typical patterns of lenses distortion. Source: NGSIM manual.

Nevertheless, a known error is not an error. Thus, with proper calibration of every camera involved in the study, a file with the distortion information for every camera was created in order to “undo” this distortion via the software.

The main problem was not the difficulty of the calibration, but the access to the camera, because the calibration is usually done with some kind of chessboard placed close to the camera, at a distance of about 0.5m. Furthermore, cameras are usually placed on a pole 12m above the freeway. After this process was done, the camera had to be immobile. However, as it is described in section “5 Incidences and suggestion for the traffic management administration (SCT) and traffic management center TMC”, when working with the SCT this is almost impossible because the cameras are used for traffic surveillance.

3.2.2 Stabilization and rectification of the video

After the cameras had been calibrated, it was time to record in the experimental field, the freeway. However, the videos obtained tend to have interference from traffic vibrations or wind, and this has to be removed using the software. The program recommended in the NGSIM manual for doing this is SteadyHand.

Once the video is stabilized, it needs to be rectified. This involves converting the conic perspective of the framing of the camera to an aerial image. This is important because it is aimed that every pixel in the video represents the same area in the real world, so the same length and width are represented. This process is designed to ease data treatment after the video analysis. A clear example of what this operation consists of can be seen in Figure 7.

3.2.3 Using geo-referenced images to position the vehicles exactly

This action consists of generating an image correspondence between the video image and a world-coordinate GIS map. This is done by obtaining a geo-referenced orthophoto of the study area and the correspondence is done with the ArcGIS software, as recommended on the NGSIM manual.

ArcGIS software was the break point, mainly because after some hours following the steps described on the NGSIM manual and the help option of the software, the progress made was almost zero. This, plus the remaining problems, represented the end of this path. The time and effort needed to make this software work properly were beyond the available means.

TABLE 2 Example of video stabilization from the NGSIM manual. An example of video stabilization can be seen at <http://www.youtube.com/watch?v=IGP7IaB8p4E>
 Source: NGSIM manual

Frame	Original Video	Stabilized Video	Cropping
Frame 1: Camera centered on stabilization object (house inside the square)			None
Frame 2: Camera moved to the right, stabilization object now in upper left corner			Cropping to the top and to the right, due to camera movement



a)



b)

FIGURE 7 Example of video rectification. a) Image as recorded of the camera, inside the turquoise rectangle the area to be rectified. b) Rectified image from the previous recording. Images from NGSIM manual corresponding to the I-80 experiment.

Moreover, the NGSIM option is extremely useful when 100% camera coverage is available, so it is possible to follow one car through the whole corridor. However, B-23 freeway case study has low level of camera coverage, so this information is only known for some stretches of the freeway.

3.3 SOFTWARE FROM ANTHONY PATIRE

The following option was software developed by Anthony Patire for a specific study site on the Tomei expressway access to Tokyo in Japan for his PhD thesis [2]. First, a simplified description of this follows. This software works with images from 11 cameras spaced about 100 meters from each other. From this, it automatically recognizes the cars in every camera using the process explained below, and some manual clicks. Thus, the software can obtain the vehicle trajectory, but without the precision of NGSIM, as the information with this method is discrete. The lane counting is still done with an error that seems acceptable, although a detailed study of the error is required to verify the hypothesis.

This software, programmed in Matlab, consists of 4 different parts: epochs, ghosts, Vid2 and tview. The “epochs” are series of images that sums up the video information, which consists in taking a horizontal line of pixels, so it is like fixing a y coordinate also called by Anthony Patire as a “the scan line”, which is accumulated through the time at the video frame rate. See Figure 7 for a clear graphic visualization.

Before the process starts, some information about the video has to be introduced, such as the video file path and name, the video resolution, the scan line coordinate. After this, the series of images is generated automatically.

Once the epoch is created, it is the moment to generate the ghosts. This process “only” consists of generating a black and white image from the epoch where the background is black and the cars are white. This only takes place in order to make the following step easier, so the software can recognize the vehicles automatically.

Vid2 and tview are the parts of the software where the manual action takes place. So, with a Graphic User Interface, the researcher has to click on every single car in the image from the first camera. Then, with the following cameras, the software makes some hypotheses in order to recognize the cars automatically. These hypotheses are that all the cars reach the following section and that all vehicles remain in the same lane in the same order. Nevertheless, if the software guesses the car position correctly, one more click is needed for each camera; otherwise 3 clicks will be needed for every single car guessed wrongly. After these steps, the trajectory data and its detailed analysis are stored.

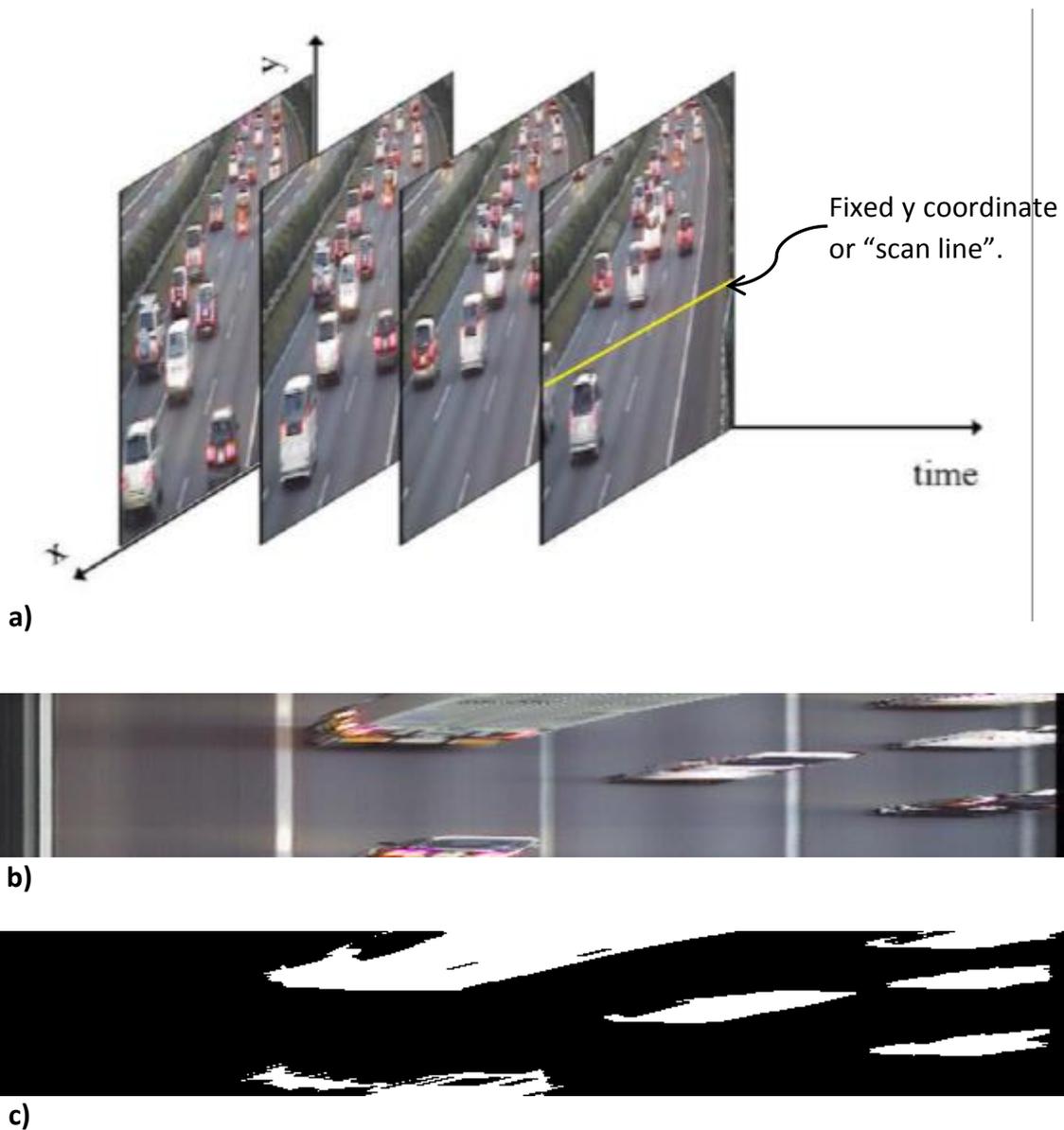


FIGURE 8 Transformation from video to epochs and ghosts. *a) Series of frames, this figure shows the video frames over time, in yellow the line that represents the scan line. b) A resulting epoch accumulating the scan line over time. c) Ghost of the epoch shown at b).*

After trying to use the software with the original data and also with some earlier data from the B-23 freeway provided by the SCT, as expected, some problems arose. However, after a detailed and calm analysis of the pros and cons of the different options, one idea emerged over all the other ones.

3.4 THE CHOSEN OPTION: ADAPTATION OF THE EPOCHS FOR A VISUAL LANE-CHANGING COUNTING

The idea was to adapt the epochs used by Anthony Patire in his PhD thesis to a vertical epoch, where the line of pixels accumulated over time would be the space between lanes. In order to achieve this, the code had to be extensively modified in the following fields.

1. Taking a vertical line instead of an horizontal one
2. Enabling the option of having a bent line, or an approximation to a curved line through a succession of different bent lines.
3. To modify the length of the epoch in time (note that now it is the x axis) in order to get a known length of time, we decided for a 1-minute period, but the option of choosing a different length was easily enabled.

After this long process, a satisfactory result was finally obtained, and this is shown in Figure 9.

The option of using this software exactly as it was designed was discarded because, while the experimental site on the Tomei toll expressway has no on- or off-ramps, the B-23 freeway has many, and the cameras are spaced much further apart. So, almost a new code had to be programmed with no guarantee that the end result would be similar to that obtained by Anthony Patire in his PhD thesis. Note that the epochs of Anthony Patire can be used for a manual car counting, as a traffic detector does, but not to count lane-changing maneuvers.

One must bear in mind that this method has two major drawbacks. One is the time needed to process the video in order to generate the epochs. This was about three times the duration of the video. This factor depends on the video (quality, format and frames per second) and the computer used for the processing. However, the computer is fully usable during this process because the algorithm used is written in a sequential order, and a step only takes place if the previous one has finished. Thus, it does not consume all the resources available in the computer.

The other drawback is that the cameras have to be configured in a predetermined way. If not, it is totally impossible to count the lane changes with enough accuracy. Thus, some vehicles, usually the bigger ones, can appear in the epoch without implying a lane changing. We named this phenomenon "occlusion". However, the following recommendations make it easy to build an epoch that facilitates the differentiation between lane changing and occlusions. The camera configuration criterion for a semiautomatic counting is explained below. We must also bear in mind that the more optimal the camera configuration is the less time is required to count the lane changes. So, for future projects that consider the use of this semi-automatic car lane-

changing count method, it is highly recommended that no more than one setting is near the minimum value, and that each camera is always tested for a few minutes.

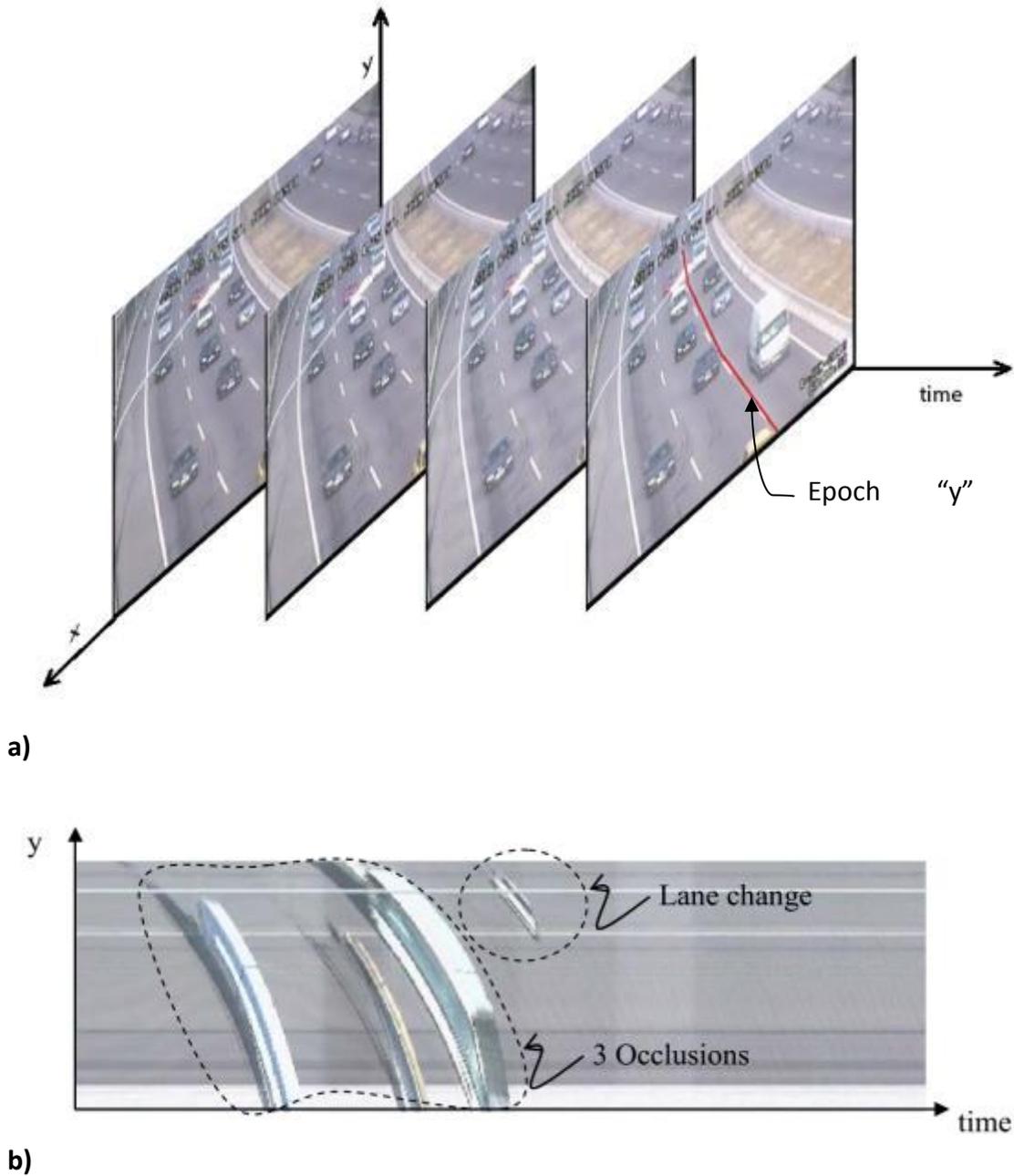


FIGURE 9 Epochs for visual lane changing count. a) Epoch construction, the red line is the line of pixels selected to build an epoch. b) Epoch showing lane changes versus occlusions.

3.5 LANE-CHANGING EPOCH CONDITIONS

The cameras have to be perfectly focused in order to obtain the best sharpness possible. A blurry image is completely useless.

3.5.1 Video quality

For car counting, as Anthony Patire uses.

For this purpose, almost any image resolution is enough. If a person is able to see a car in the video record, they will be able to see it at the epoch. The frame rate must be over 10 frames per second (fps), and over 24 fps is recommended. The higher the resolution and fps, the easier the car counting will be, but the image processing will be slower.

For car lane changing, the new adaptation

The recommended resolution is as high as possible. Unfortunately, it was impossible to check how HD resolutions work because these were unavailable in B-23 study site, but it is still possible with lower resolutions. In this experiment, a 720x540 resolution was used, the maximum available at the SCT traffic management center (TMC). A minimum resolution of 320x240 has to be considered, but with this low video quality, it might be almost impossible to count the car lane-changing in some scenarios, and the counting error could be unacceptable. Moreover, the time saving from totally manually count would be inappreciable.

The frame rate has to be over 10 fps and a rate of over 24 fps is recommended for a clear and error-free counting.

Video frame:

The image has to be only of the freeway, as all the pixels are needed for the road. The sky or trees surrounding the freeway do nothing for this use. There are examples in Table 3.

The visible freeway length in the chosen frame has to be clearly higher than the length of the lane-changing maneuver. To give an approximate value, a length greater than 50 meters is recommended. This is to recognize the occultation and lane change clearly.

The frame angle has to be as parallel as possible to the line dividing lanes. With this kind of framing, it is possible to look clearly at the line and it keeps possible occlusions due to high vehicles or ones that are circulating on the edge of the lane to a minimum. See Table 4.

TABLE 3 Freeway framing.



TABLE 4 Examples of video frame angle.



As a consequence of the previous conditions, a correct framing usually includes a stretch of freeway at least 100 meters from the recording point (the camera site) and at a maximum of around 500 m

- The epoch length has to be much greater than the time a lane-change usually takes. The aim is that almost all the lane changes take place in the same epoch, thus minimizing the counting errors that may arise when a lane-changing maneuver is spread over two or more epochs. For this case, a length of one minute was used being long enough to satisfy the previous condition and it is the same period of time that traffic detectors use to aggregate the data.
- Use only daylight. One test was carried out with a night light conditions, but, due to the vehicle headlights, the resulting epochs were absolutely useless. In addition, take care that the cameras are not dazzled by the sun. This happened the first day during sunrise with all the cameras pointing east, so a recommendation is not to point the cameras at the sun.
- Bad weather, such as fog or rain, is not recommended. However, with some equipment, this may not be a problem. On the B-23, two problems were detected. One was that cameras were wet so the image was blurry, and the

other one was that traffic demand and behavior is not guaranteed to be consistent with that under good weather conditions.

3.6 CONCLUSIONS FROM THE CHOSEN METHOD

After using this method for the 7 valid days of the experiment (see Soriguera, F. and M. Sala. (2013). *Dynamic Speed Limits on Freeways: Experiment and Database*) the results were quite satisfactory and enough time was saved (excluding the development time of the tool) to justify the effort of this video transformation. It is estimated that this process reduced total human observation time by about 90% compared to the time-consuming activity of actually watching the videos. With some cameras, on some days, technical issues arose and, as a result, video quality was affected, although the estimated time saving was still over 75 % compared with watching the videos.

4 EXPERIMENT DESIGN

4.1 PREVIOUS ANALYSIS

After the layout was finished, and it was known how to extract the data needed from the video recordings, the next step was to design the experiment. This part is widely explained at Soriguera, F. and M. Sala. (2013). *Dynamic Speed Limits on Freeways: Experiment and Database* [1].

First of all, a 24 hour traffic analysis was made. The data for this analysis was taken from 0:00 to 24:00 on 12th December of 2012. It can be found at [4] and have a detailed analysis of the placement of 5 different bottlenecks that have been detected. The bottlenecks are characterized by its activations, deactivations, capacity drop and maximum capacities.

Nevertheless, what was really necessary was a rough analysis of various days in order to know when the inbound rush hour happens. As further explained in chapter 5, the shorter the experiment was, the better for the SCT. Nevertheless, without taking the whole rush hour, a huge amount of information was lost, so it was a difficult compromise to reach.

With the aim of knowing this, a little study was done. The information available to do it was from 3 weekdays at the end of January 2013 and other 4 weekdays at the beginning of February 2013.

The conclusions were:

- Recurrent congestion appears at 2 km closest to Barcelona about 7:30 and ends at 9:30 or so.
- Some days at PK 7,5, where the freeway diverges to Barcelona south beltway, a huge congestion appears only after 8:30 and spreads fast to the end of the study site. It is supposed that this occurs when some incidence takes place at Barcelona south beltway and heavy congestion happens affecting everything that is upstream.
- High dense traffic is observed at PK 3.5 where S11 is. After the experiment it was quite clear from the video recordings from the camera 2305 that it was an exit bottleneck with spillback.

Contour plots that justify the previous conclusions can be found at appendix A2.

Knowing all this, the decision was to schedule the experiment between 7:00 to 10:00, almost ensuring that all the rush hour congestion were included. Otherwise, without the analysis the experiment had to be set from 6:00 to 11:00, so a reduction of 2 hours per day was achieved.

Even more, these analysis showed where to focus the experiment, and thus which cameras were selected for recording, where to frame them and which detectors were selected for individual recording.

4.2 CONDITIONS FOR THE EXPERIMENT

SCT was able to deliver the following information for each day: 3 TV camera records, minute lane aggregations for all detectors, individual actuations for 4 detectors (raw detectors), the LPR system data and the DSL limits

Moreover, the traffic administration imposed some additional restrictions to the experiment in order not penalize travel time in excess. This includes a minimum of 50 Km/h speed limits in free flowing sections, and a maximum length of 5 Km where this minimum speed limit could be posted simultaneously.

The first idea was to do the experiment as one corridor, but after these tight restrictions, it seemed better to do it as two different ones. The first part is the one closer to Barcelona, and the other one is the farthest one.

With this option, more information could be recorded, so 4 detectors and 3 cameras were recorded for each part. So, it was as if 8 detectors and 6 cameras were available. The con was that they were on different days, so the traffic might change.

4.2.1 Raw detectors

To decide the raw detectors, the most important criteria was having the raw data for the section with a Radar (a speed enforcement device), plus another one just downstream from the radar. The other two were chosen in an intuitive way from data of the traffic analysis previously done.

4.2.2 Cameras

The camera selection was done because of their situation and because they were the ones with the better vision of the freeway, so the methods of video processing previously explained could be used. The ones that were not suitable for using the semiautomatic post processing were automatically discarded regardless of their location.



FIGURE 10 Chart of screenshots of the camera framing.

4.2.3 Speed limits

The speed limits chosen for the experiment can be seen at the Table 5. The criteria to set up those limits were.

1. The higher limit possible (80 Km/h inner, 100 Km/h outer).
2. The minimum limit possible (40 Km/h inner, 50 Km/h outer).
3. An intermediate scenario between 1 and 2 (60 Km/h inner, 80 Km/h outer).

When low speed limits were applied to the inner part (60 and 40 Km/h), the decision was to set a 80-Km/h speed limit instead of 100 Km/h at the outer part with the aim of making the transition between both parts as smooth as possible.

TABLE 5 DSL and surveillance equipment configuration for experiment

		Day#1	Day#2	Day#3	Day#4	Day#5	Day#6	Day#7
Dynamic Speed Limit Gantries	33-66 PVV	Upstream transitional speed limits.						
	32-67 PVV							
	32 PVV	SCT	100	80	50	100	80	80
	30 PVV	SCT	100	80	50	100	80	80
	29 PVV L	SCT	100	80	50	100	80	80
	27 PVV	SCT	100	80	50	100	80	80
	24 PVV	SCT	100	80	50	100	80	80
	22 PVV	SCT	100	80	50	100	80	80
	20 PVV	SCT	80	80	50	80	80	80
	18 PVV	SCT	80	80	80	80	80	80
	17 PVV	SCT	80	80	80	80	80	60
	17 PVV L01	SCT	80	80	80	80	80	60
	17 PVV L02	SCT	80	80	80	80	80	60
	13 PVV	SCT	80	80	80	80	60	40
	11 PVV	SCT	80	80	80	80	60	40
	08 PVV	SCT	80	80	80	80	60	40
	06 PVV	SCT	80	80	80	80	60	40
	04 PVV	SCT	80	80	80	80	60	40
	03 PVV	SCT	60	60	60	60	60	40
02 PVV	SCT	50	50	50	50	50	40	
TV Cameras (High quality: 30 fps and 536 x 400 pixels)		2306	2312	2312	2312	2306	2306	2306
		2305	2310	2310	2310	2305	2305	2305
		2304	2309	2309	2309	2304	2304	2304
Raw Detectors (Individual actuations) (ETD – Double Loop detector) (DT – Non Intrusive Detector)		13(DT)	30 (DT)	30 (DT)	30 (DT)	13 (DT)	13 (DT)	13 (DT)
		12 (Loop)	27 (Loop)	27 (Loop)	27 (Loop)	12 (Loop)	12 (Loop)	12 (Loop)
		11 (DT)	21 (Loop)	21 (Loop)	21 (Loop)	11 (DT)	11 (DT)	11 (DT)
		8 (DT)	19 (Loop)	19 (Loop)	19 (Loop)	8 (DT)	8 (DT)	8 (DT)

5 DATA ACQUIREMENT: THE EXPERIMENT

After the long planning previously narrated, the experiment was finally carried out on Tuesdays, Wednesdays and Thursdays between 30th May 2013 and 19th June 2013.

At the same time as the experiment was taking place, some data processing had to be done with the aim of checking the reliability of the data acquired during the 3-hour experiment.

The data for each single day is:

- The minute aggregation data for all lanes at section with traffic detectors.
- Individual data from selected detectors.
- Maximum speed shown at each PVV gantry for every minute of the experiment.
- The matching of the LPR system, giving the measured travel time.
- The video recordings from the selected cameras for the 3 hours of the experiment.

When an unacceptable gap or error of the data happened, such as recording with the wrong camera, the data for this day had to be rejected and repeated until it was acceptable.

TABLE 6 Experiment Development

Experiment configuration	Date	Result	Incidents
Day#1	Thu. 30 th May 2013	Fail	-TV cameras 2304 and 2305 => wrong focus, low quality (320x240 pixels). -TV camera 2306 => wrong focus.
Day#1	Tue. 4 th June 2013	Correct	-33 ETD => Speed missing for Lane 1 between 7:00 and 8:55am.
Day#4	Wed. 5 th May 2013	Fail	-Wrong speed limit at 32 PVV. -Recording TV camera 2311 instead of 2312. -Individual actuations of detectors 26, 25, 24 and 23 ETD instead of 30, 27, 21 and 19 ETD.
Day#5	Thu. 6 th June 2013	Correct	
Day#3	Tue. 11 th June 2013	Correct	-TV camera 2310 => 30 minutes of low quality.
Day#4	Wed. 12 th June 2013	Correct	
Day#6	Thu. 13 th June 2013	Correct	
Day#7	Tue. 18 th June 2013	Correct	-13 ETD(DT) => Vehicle count malfunctioning. Approximately 4 000 vehicles are lost, mainly on Lane 1, during the 3h of the experiment (28%).
Day#2	Wed. 19 th June 2013	Correct	

As explained at appendix A1, the DT traffic detectors have some drawbacks, so everywhere a simple loop detector was placed in the same place; data from both were collected so the end result was more accurate.

6 DATA TREATMENT AND OVERVIEW

6.1 DATA TREATMENT

The data treatment was done with Matlab software. This software was chosen because it is known to be capable of managing large amounts of data and it can read the Microsoft Excel files easily (all the data except the videos were given in Microsoft Excel files). Besides, once one given algorithm is programmed, for instance one day's data process, it can easily be repeated many times. It is not the only software that has these characteristics.

First of all, a Matlab file with all the section information needed at the following scripts was written to do the data check. In order to avoid doing an enormous uncompressible script, the code was split into different scripts and functions to make it more comprehensive. Therefore, a general mother script which calls all the other ones had to be done.

Following area brief description of all the data collected and how it was processed and afterwards a detailed schema of how it was stored.

6.1.1 Minute aggregated data

This data is the minute aggregation for each detector and lane, so there are 3 numbers for each: occupation, speed and flow.

The first step was to read the files where the data is stored. However, there were some detectors with double data, one with ETD (DT) technology and another with simple loop technology ETD (S). See figure 4, and appendix A1 for more details. For those detectors with both DT and S information, DT was the selected source for the speed information, and S for the occupancy and vehicle counting. At this point, an aggregation of the data per section for each minute proceeded as shown in the following formulas.

$$Flow = \sum_{i=1}^{\# \text{ lanes}} Flow_i$$
$$Speed = \frac{\sum_{i=1}^{\# \text{ lanes}} speed_i \cdot flow_i}{Flow}$$
$$Occupancy = \frac{\sum_{i=1}^{\# \text{ lanes}} occupancy_i}{\# \text{ lanes}}$$

6.1.2 Raw data

For some detectors, as seen at 4.2 Conditions for the experiment, raw data was available. This data is a huge list with all the vehicles that the detectors have detected in all the different lanes. Each lane has a number that identifies it. One of the list fields is the lane identification number for each vehicle so it is possible to know in which lane the vehicle has been detected.

Writing a proper algorithm to process the individual data and save it in an orderly manner was the most difficult point at this stage of the experiment. Many versions had to be done, because every time that some extra verification was wanted, some big changes were needed.

In spite of these technical difficulties, the logic behind this process is pretty simple. First, all the data was read. Note that data from all detectors come from the same file. Secondly the different detectors were separated and the raw data was saved. Finally, the time stamp to do a minute aggregation was read.

In order to be able to compare the raw data with the minute aggregated data, a minute and section aggregation of this data was done. This aggregation of this data is much simpler than the minute aggregated data per lane. The reason is that we have all the data, so:

$$\begin{aligned} \text{Flow} &= \# \text{ minute} \\ \text{Speed} &= \frac{\sum_{i=1}^{\# \text{ minute}} \text{speed}_i}{\# \text{ minute}} \\ \text{Occupancy} &= \frac{\sum_{i=1}^{\# \text{ minute}} \text{occupancy}_i}{\# \text{ lanes}} \end{aligned}$$

Note: #minute is the total individual vehicles in a given minute for all the lanes, and it is a known data. No lane classification was done at this point.

6.1.3 Error between raw data and minute aggregated data

As it is widely explained in appendix A1, detectors on the B-23 freeway saving individual detecting can undercount vehicles due to hardware limitations. So with the aim of knowing how much this happens and if it was acceptable or unacceptable, a series of graphics were built (Figure 16). To successfully achieve the construction of these graphics, some calculus had to be done. First of all, the calculation of the total error, that is very simple. For one given minute of the experiment and one given variable, the error is the minute aggregation data value minus the aggregated individual data for the minute and variable. So the following formula applies.

$$\text{Error}_i = \text{minute_data}_i - \text{individual_data}_i$$

Once this calculation is done it is possible to see that most of the errors are quite small, nevertheless a few minutes have extremely large errors. Thus, it is interesting to set an error threshold, above of which the error is considered unacceptable for those minutes. The thresholds for each variable are established at ± 5 for flow speed and ± 2 occupancy. Then it is possible to count how many minutes have an error over them. This way, the researcher can easily obtain an idea about the quality of the individual measurements for each traffic detector. See Table 8.

Note that all the comparisons were made from data obtained at the same detector. As an example, the flow error for 08 ETD was calculated by comparing individual data from 08 ETD (DT) to the minute aggregated data of the same 08 ETD (DT), not the one from 08 ETD (S). This procedure was followed because the final goal was to check the reliability of individual data vs minute data, not between different technologies. So to know how many actuations were lost with individual recording.

6.1.4 DSL

The DSL data is as simple as a table with the speed limits actually posted at the freeway gantries. It is one number per minute and gantry. No treatment is done to this data.

6.1.5 LPR

The data from the License Plate Recognition system was stored and introduced to the experiment data. The operational behind this system of data is simple; two detectors are able to automatically read license plates, which are spaced apart. See figure 4 for details of where the LPR are placed.

The operation is as follows, when a vehicle that has passed through the first LPR reaches the second one, the system automatically calculates the travel time and stores the data. If more than one vehicle is available for one minute, an average travel time is calculated. If there is only one, the time of this vehicle is the travel time, and if no vehicle is matched, the system gives us a 0 minutes value. Note that the system does not read all the license plates, so, the 0 scenario can happen.

For every day this data is a 180 number list, 1 per each minute. The only treatment given to this data was change the 0 values to a NaN (Not a Number) to make even clearer that there was not any match.

6.1.6 Lane free speed

For data overview purposes it is necessary to have the value of the free speed in each lane and section. However, this data cannot be measured directly. It is a computed data from the minute aggregated data. Usually, it is measured when low occupancy and flow happens. As this is not going to happen in the morning rush hour, the

following criteria were followed for each lane, in order to determinate which was the free speed value.

1. Identify the 30 minutes (not consecutive) with the fastest speeds.
2. Sort the previous 30 minutes from the fastest to the slowest.
3. Take the median value as the free speed.

The time interval to compute these free speeds was from 7:05 to 10:00. An exception was made for the day#4 and the values were taken from 7:15 to 10:00. These times are not 7:00 because of the time consumed posting the transitional speeds until the planned ones were achieved.

With all the previous steps done, a lane free speed value is achieved, although the section free speed is still unknown. So a weighted average between lane free speeds is done. The weight is the flow in the 30 fastest minutes previously considered for each lane.

$$Flow_{30} = \sum_{i=1}^{30} Flow_i$$

$$Sectional\ Free\ Speed = \frac{\sum_{i=1}^{\#lanes} (Flow_{30} \cdot Free\ Speed)_i}{\sum_{i=1}^{\#lanes} Flow_{30_i}}$$

6.1.7 Daily demand

Using the minute aggregated data and a proper stretching of the freeway it is possible to calculate the daily demand. So the total demand is the result of summing, for the stretches, the multiplication of all the vehicles that passed the detector section by its length.

$$Demand = \sum_{i=1}^n \# Veh_i \cdot Length_i$$

However, the stretches boundaries have not been defined yet. For this purpose, the freeway was divided following the given criteria.

- Every detector, whatever the technology, defines ones stretch
- The detector is inside the stretch and its borderline upstream and downstream were defined by:
 - If no PVV, E or S is placed between two consecutive detectors, the boundary is defined by the midpoint between them.
 - If there is no E or S, but a PVV, the last one defines the stretch boundary.
 - If there is an E or S between two consecutive detectors, the last one defines the stretch boundary, having priority over all the previous criteria.

- If there is more than one E or S between two consecutive detectors, there is a problem. One of them defines the boundary and the error which happens is accepted.

With all the previous, the freeway was divided into stretches and the length of each stretch assigned to the corresponding detector. So the total demand is calculated and stored.

6.1.8 Data storage

Once all kinds of data have been introduced in detail, the next step is to explain the method developed at CENIT to keep data organized. It is quite simple. It consists in saving the data into a Matlab structure following a hierarchical schema. The following schema presented is the adaptation of this method to the particular data case of the present experiment. A schema with the names of each level of hierarchical structure, and a brief description of the different elements is detailed below.

- b23
 - section_info
 - ETD_list (list of all the traffic detectors).
 - DSL (PVV gantries information).
 - Excel_list (file names of the excel files that contain information of ETD, PVV, LPR and individual data).
 - Lane_list (number of lanes for each section).
 - dayDDMMYYYY (DD is the day number, MM the month number and YYYY the year number, ie. day04062013).
 - sXX_ETD (XX is the ETD number, ie. s02ETD).
 - minute
 - laneX (X is the lane number, ie. lane1).
 - 180x3 matrix (columns are vehicle count, speed and occupancy, rows are minutes).
 - Free_spd
 - laneX
 - 2 values. Flow₃₀ and free speed.
 - Agr_minute (180x3 matrix, same as per lane however the values correspond to the aggregate section).
 - Cum_flow (total vehicle count for the section thought the 180 minutes, only one number).

If also individual data is available.

- Individual
 - Raw_data (unprocessed data with all the vehicles actuations).
- Agr_i (like the agr_minute, but the aggregation is made from the individual raw data).
- Err (180x3 matrix, with the error between minute and individual data, for the section value and each minute).
- Err_threshold (3 values which are the % of minutes over the fixed threshold for each variable).
 - DSL (a matrix for the 20 PVV signs and 180 minutes with the speed shown for each sign and minute)
 - LPR (a vector with the travel time for the 180 minutes)
 - Demand (value of the demand in that day)

This could seem very simple, but it is not obvious and it is very useful because of its flexibility that allows saving very different type of data with different sizes under the same file.

6.2 DATA OVERVIEW

After introducing all the data involved in the experiment and how it has been processed, it is the time to look at what all these data represents. With the aim of making an easier read, as the original data with thousands of fields are difficult to understand even for who have built it, some graphics and summary tables have been done.

6.2.1 Total freeway demand

The first is the freeway daily total demand. This is one single value for each day with the total vehicles kilometer. This value is very important as there are different scenarios with different speed limits and these can only be compared if the total demand in all different days is similar. The downside is that it only says how many vehicles have moved in the freeway, and not how they have done it. This is the price paid to summarize a day in a single number.

TABLE 7 Traffic demand on the experiment site during the morning rush

Experiment configuration	Total demand (veh·Km)	Relative difference to the average
Day#1	166156	-0.9 %
Day#2	168317	0.4 %
Day#3	166342	-0.8 %
Day#4	167624	0.0 %
Day#5	168015	0.2 %
Day#6	167719	0.1 %
Day#7	169074	0.9 %
Average	167608	

It is easy to see that all the values in table 7 have minimal differences, so the conclusion is that the demand for all the experiment days in the freeway has been similar.

6.2.2 Corridor time averages

Just after seeing the overview for the demand it is time to add some detail in order to see the basic operation of the freeway along the experiment site. For this purpose the free speed is considered, as well as the averages of occupancy and density for the 180 minute that experiment lasts for each section. These data is placed in a plot where the space is the x-axis and the magnitude of the data is represented in the y-axis.

In the accumulated vehicle count or flow it is easy to see the most demanded on and off-ramps. In B-23, it is clear that these are the ones which connect with the Barcelona beltways (S7, E8 and S14). Following the traffic direction it can be seen that in the first half of the freeway, traffic increases and at second one, it decreases.

In the occupancy plot, the higher values for all the days correspond to the most congested areas. In fact, these are the ones predicted in the preliminary study, the exit 7, exit 11 and Barcelona city entrance.

Finally, explaining the free speed plot, it is possible to see that as vehicles are getting closer to Barcelona the free speed decreases. Also, the “V” shape around radars (speed enforcement devices) is quite remarkable, drivers brake before the radar and throttle after it. Despite of the speeding, the free speed is lower when lower speed limits apply. This is a picture of how traffic behaves in the freeway.

6.2.3 Total travel time

Keeping the same detail, but focusing in time instead of space, there are LPR data, which allow visualizing the travel time changes through time. This data is very easy to see when bigger delays happened. Putting the LPR data for all days in one single plot, a very visual and easy comparison between different day's delays is achieved.

In the case of the B-23 freeway, travel time at 7:00 a.m. is approximately free flow time. Every day, it starts increasing smoothly from then and until about 7:45 a.m. At this time and depending on some still unknown factors, on some days travel time keeps increasing even faster until 8:30 a.m., and it is not until 10:00 a.m. that free flow travel time is restored. While on other days, travel time stabilizes in 10 minutes or so (4 minutes delay) for a while. By 9:15 a.m., traffic has free flow travel time again. After reading this data, it is reasonable to say that morning rush hour starts about 7:00 a.m. and finishes at 9:30 a.m.

Furthermore, looking at figures 10 and 11, it can be seen that the 3 days with higher travel times (day#3, day#4 and day#6) are the ones with higher occupancy rates in the Barcelona entrance, so data is starting to make sense.

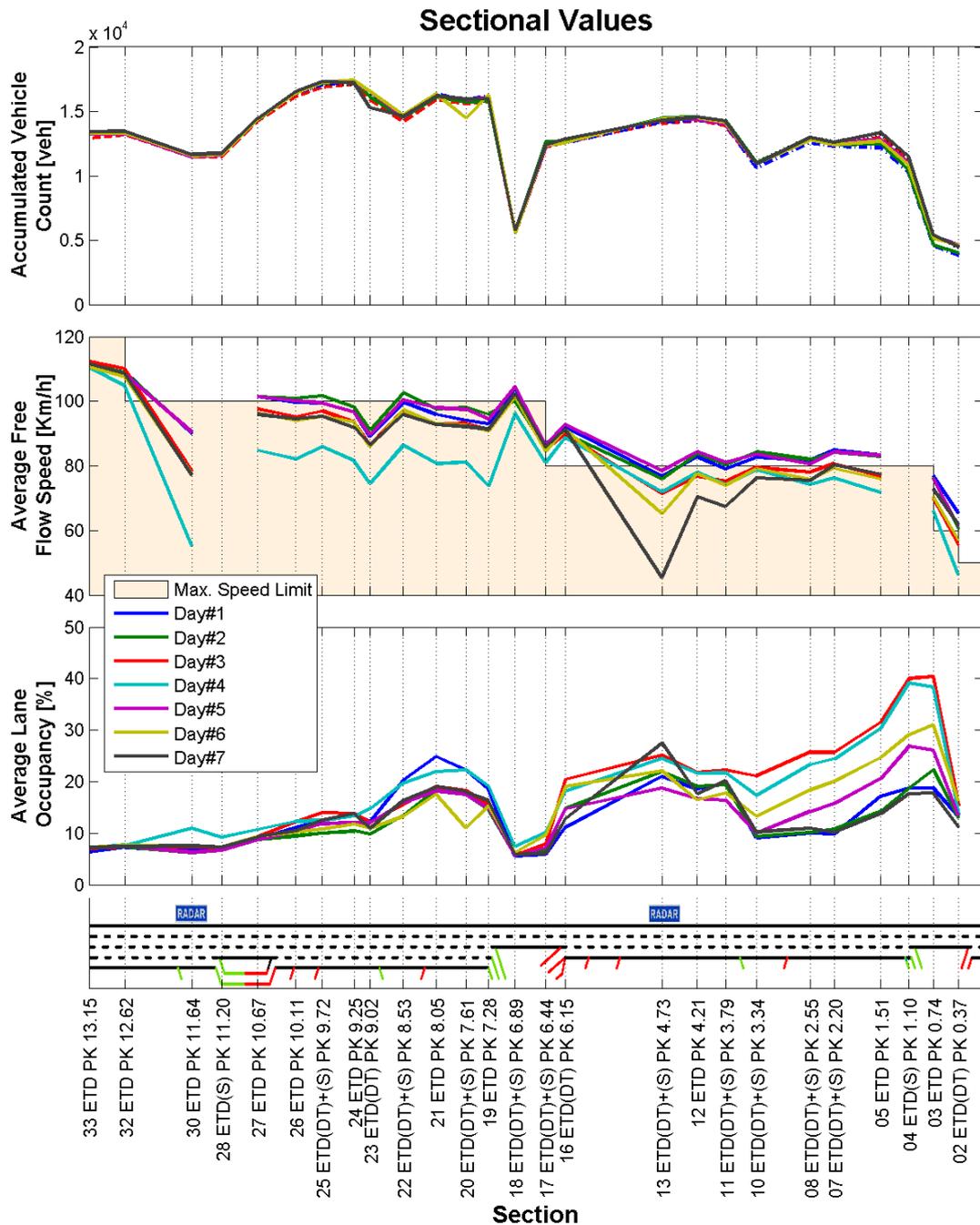


FIGURE 10 Corridor time averages for morning rush in all experiment days. a) Cumulative traffic demand. b) Average free flow speed. c) Average occupancy. (Data obtained between 7:00 and 10:00am, 04th, 06th, 11th, 12th, 13th, 18th, and 19th of June, 2013, inbound direction).

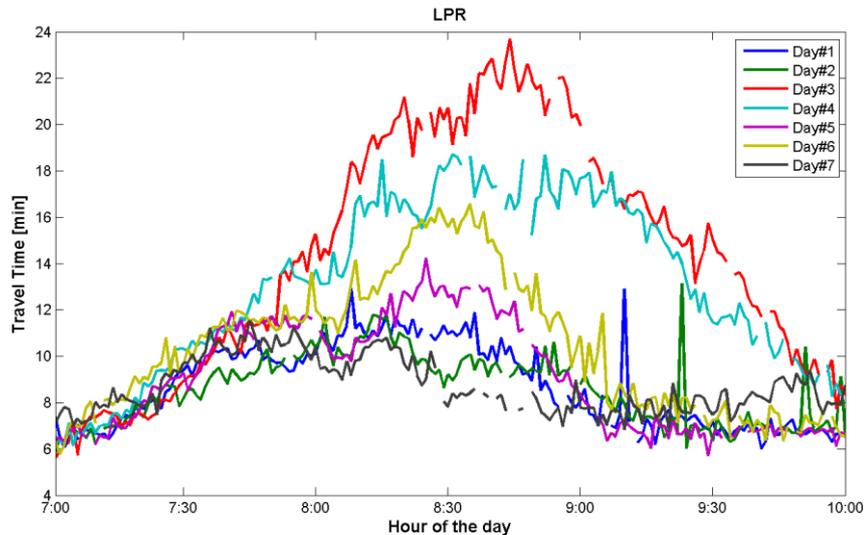


FIGURE 11 Travel time for all experiment days. *a) Example of single day travel time plot (Data obtained between 7:00 and 10:00am on Tuesday June 4th, 2013, inbound direction). b) Plot with travel time information for all days.*

6.2.4 Sectional space-time contour plots with minute aggregated data and raw data

Everything done until now is aggregated data in time or space, without details of what has happened in every moment and every point. So, to see more details of what happens over time, it is necessary to zoom in. This is achieved doing contour plots where the x-axis represents time, the y-axis space and the z-axis the value of the variable. Hence, it is a 3D graphic, but when the z-axis is transformed into a gradation of colors, it becomes 2D. These graphics are not as simple to read as the previous, but the complexity makes them richer in information.

Three contour plots (CP) were made, one for each variable (speed, flow, occupancy). They make it possible to see the traffic states changing during the 3 hours and the 13,15 Km of the experiment. Besides, the CP have been very useful, as each day after receiving the data, it was processed. Then, CP were made to quickly see what had happened on the freeway, and check possible data measurement errors.

For the CP construction, a vehicle traveling on the freeway moves from bottom-left to the top-right of the CP. The slope represents the vehicle speed. Additionally, it is possible to see the bigger shock waves propagating through the freeway. The minor ones cannot be seen because this is not for what this CP is made for.

For example, in Figure 12, in all the 3 CP, but even more clearly in the speed one, there are three shock waves going upstream in the congested traffic between 7:30 a.m. and 8:30 a.m., starting at detector 21 ETD and ending at 26 ETD. Besides, as it can be observed in the flow CP, orange and red spots appear showing very high flow, just before each shock wave happens. It is this high flow which triggers the bottleneck.

Another thing that can be seen very clearly is a low speed and high occupancy triangle between sensors 02 ETD and 06 ETD, which corresponds to the congestion closest to Barcelona. Also, for day#3, the one with more delay, all the CP are quite different from the ones on day#1, where the triangle previously commented is transformed into a bigger trapezium. All the suspicions that the entrance of Barcelona was a more restrictive bottleneck are confirmed by checking the flow CP that day. It has more bluish tones all experiment long, representing lower input flow rates in Barcelona city. See figures 12 and 14.

It is when looking at the speed CP where some behavior changing through different speed scenarios becomes more obvious. For example, in day#4, when at the outbound site the speed limit was much lower than the usual one, a significant change is appreciated. This is a more homogeneous speed, with no significant shock waves downstream from the enforcement device. However, after reaching E8, this effect disappears and large shock waves appear.

The same happens in day#7 for the closest stretch to Barcelona. From the speed enforcement device to the city entrance, not a single appreciable shock wave appears on the CP. Even more, at the outbound part, because of the transitional speed limits (80Km/h instead of the usual 100 Km/h) there is also a slight improvement. See Figure 13.

Last but not least, is checking that the data is “good looking”. In spite of some gaps it is so: all data was accepted as good enough. However, with a careful look at the occupancy, some little odd variations appear. This is because for both minute data and individual data, occupancy time for DT detectors is quite smaller. Since all inductive loops are 2.0 m long and DT the “loop length” is assumed to be 0, because no loop is present. So, “T” is the aggregation period, “ l_i ” and “ v_i ” the vehicle “i” length and speed respectively, “d” the length loop and “n” the total vehicles measure during “T”.

$$occ = \frac{1}{T} \sum_{i=1}^n \frac{l_i + d}{v_i} (x100)$$

For its similarity with the minute aggregated data it is suitable to do the overview of the raw data just after. In this case, it is only about replacing in the previous CP the minute aggregate data for minute aggregations of raw data, in those detectors where raw data was recorded. Thus, the resulting CP has to be very similar.

In fact, in these CP, most data are not from raw but from minute, since raw data is only available in four detectors (4 rows) each day. For this reason, differences will only appear in 4 rows and usually are subtle.

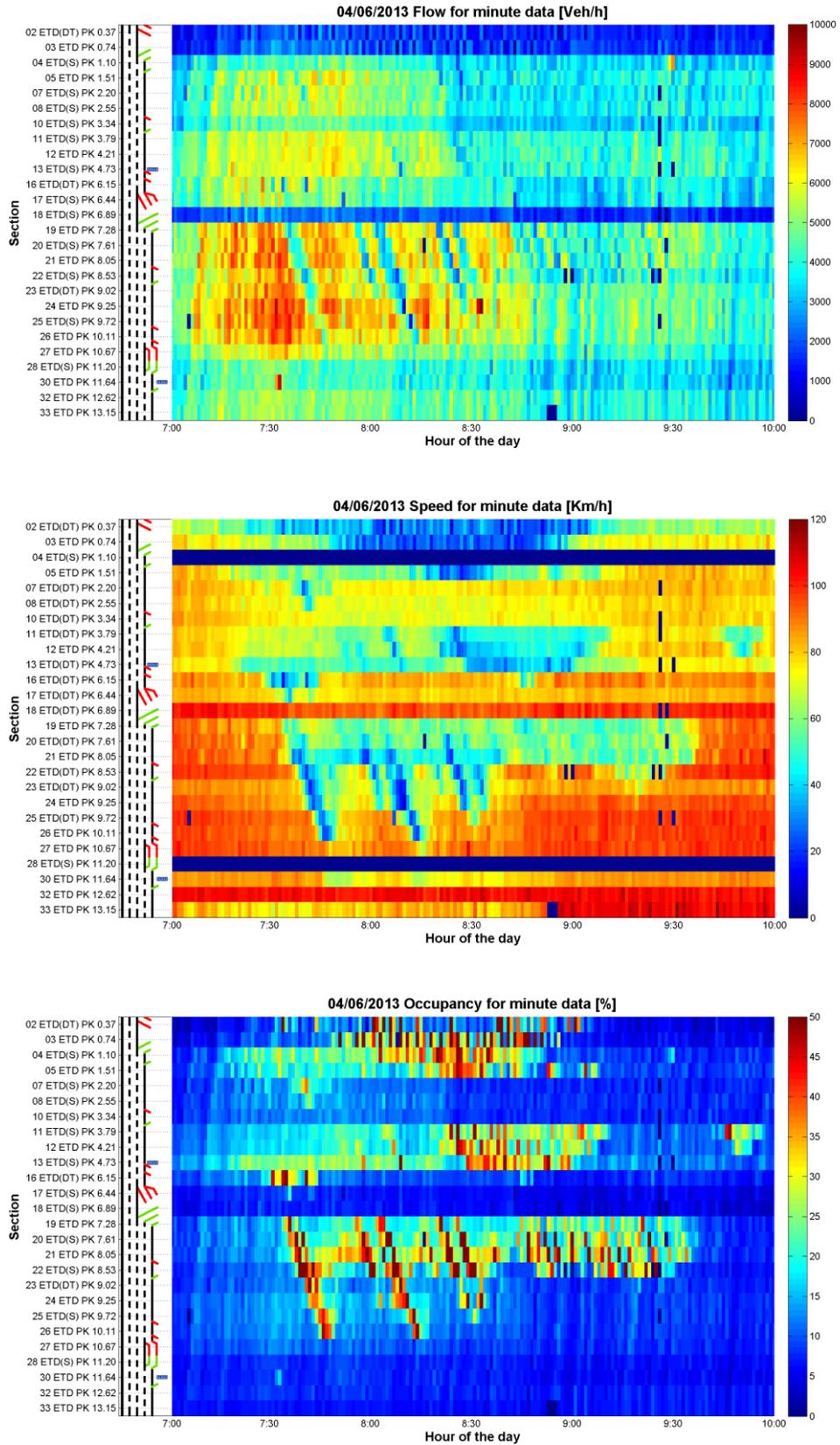
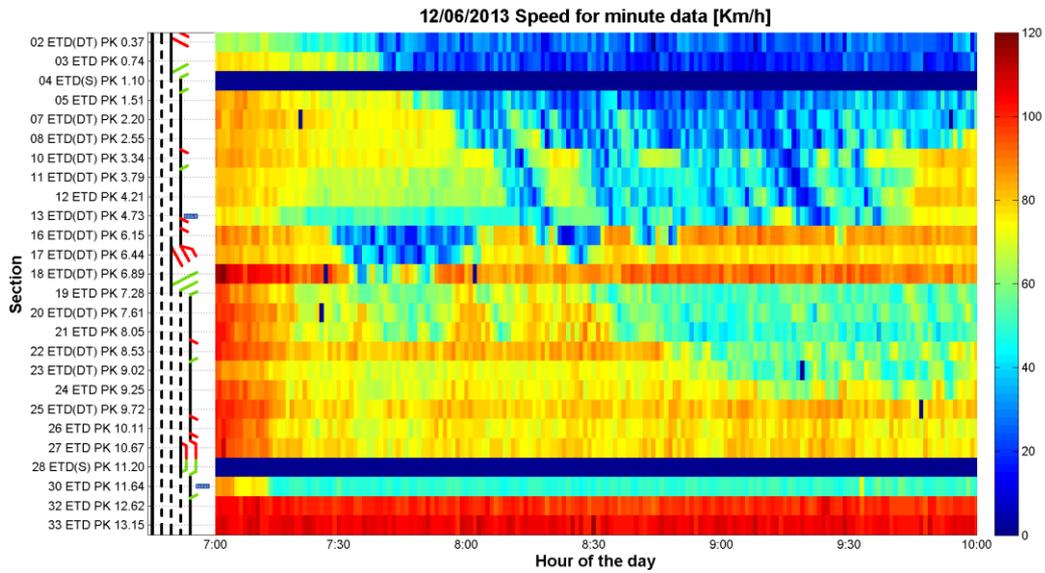
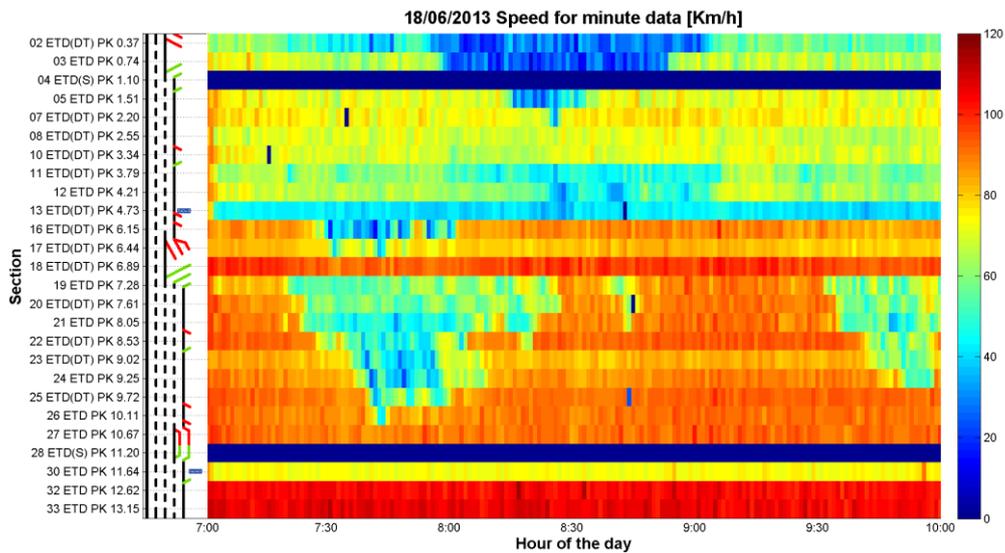


FIGURE 12 Contour plots for minute aggregated data (Data obtained between 7:00 and 10:00am on Tuesday June 4th, 2013, inbound direction).



a)



b)

FIGURE 13 Real speed differences between different speed limit scenarios. a) Day#4, outbound speed limit set at 50 Km/h (Data obtained between 7:00 and 10:00am on Wednesday June 12th, 2013, inbound direction). b) Day#7, inbound speed limit set at 40 Km/h (Data obtained between 7:00 and 10:00am on Tuesday June 18th, 2013, inbound direction).

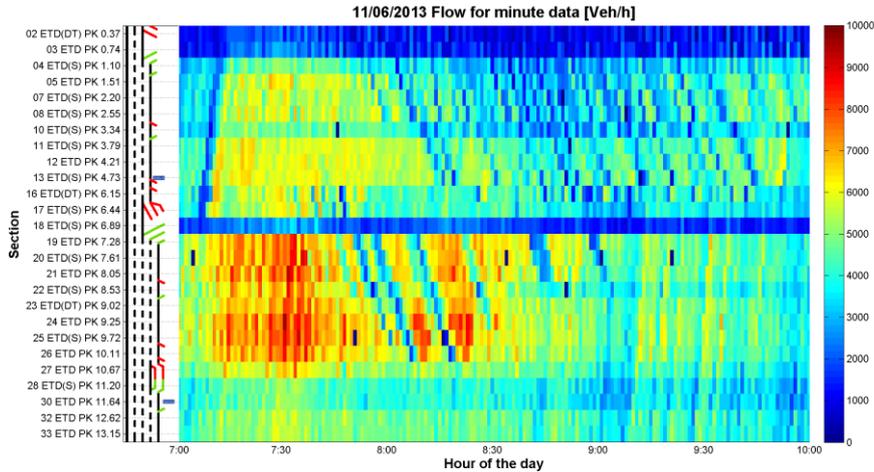


FIGURE 14 Flow contour plot when more restrictive bottleneck appears at Barcelona entrance. (Data obtained between 7:00 and 10:00am on Tuesday June 11th, 2013, inbound direction).

For the day 04/06/2013, day#1, these raw data rows correspond to the detectors 08 ETD, 11 ETD, 12 ETD and 13 ETD. Occupancy differences are the most remarkable while the speed ones are almost imperceptible. See Figure 16.

6.2.5 Error between minute aggregated data and raw data

Just because differences are really difficult to be appreciated it became necessary to make a new series of graphics. These series are based on the error calculations made at 6.1.4 Error between raw data and minute aggregated data.

In this CP, there are only the 4 detectors that have raw data. Contrary to the previous CP, in this one it is clear that the detector 12 ETD (double loop) is very reliable in terms of speed and occupancy, but very bad measuring flow. This is because the detector hardware is old and high flow exceeds its capacity, so it randomly loses some vehicles.

About the raw behavior of the other 3 detectors, all three are DT technology; it is noticeable that the flow error is much better than the error in the double loop one. Related to the speed and occupancy, detectors 11 ETD and 13 ETD have significant errors, much greater than the 08 ETD. This could be because of some particularities of this technology working in heavy traffic. See more details in appendix A1.

The plot only shows a maximum difference of +/- 10 or +/- 5, but some higher values may happen; this is made to clearly see the near 0 error without the scale distortion that high values introduce. In order to not reduce the information given, the percentage of high error minutes calculated in point 6.1 is given too.

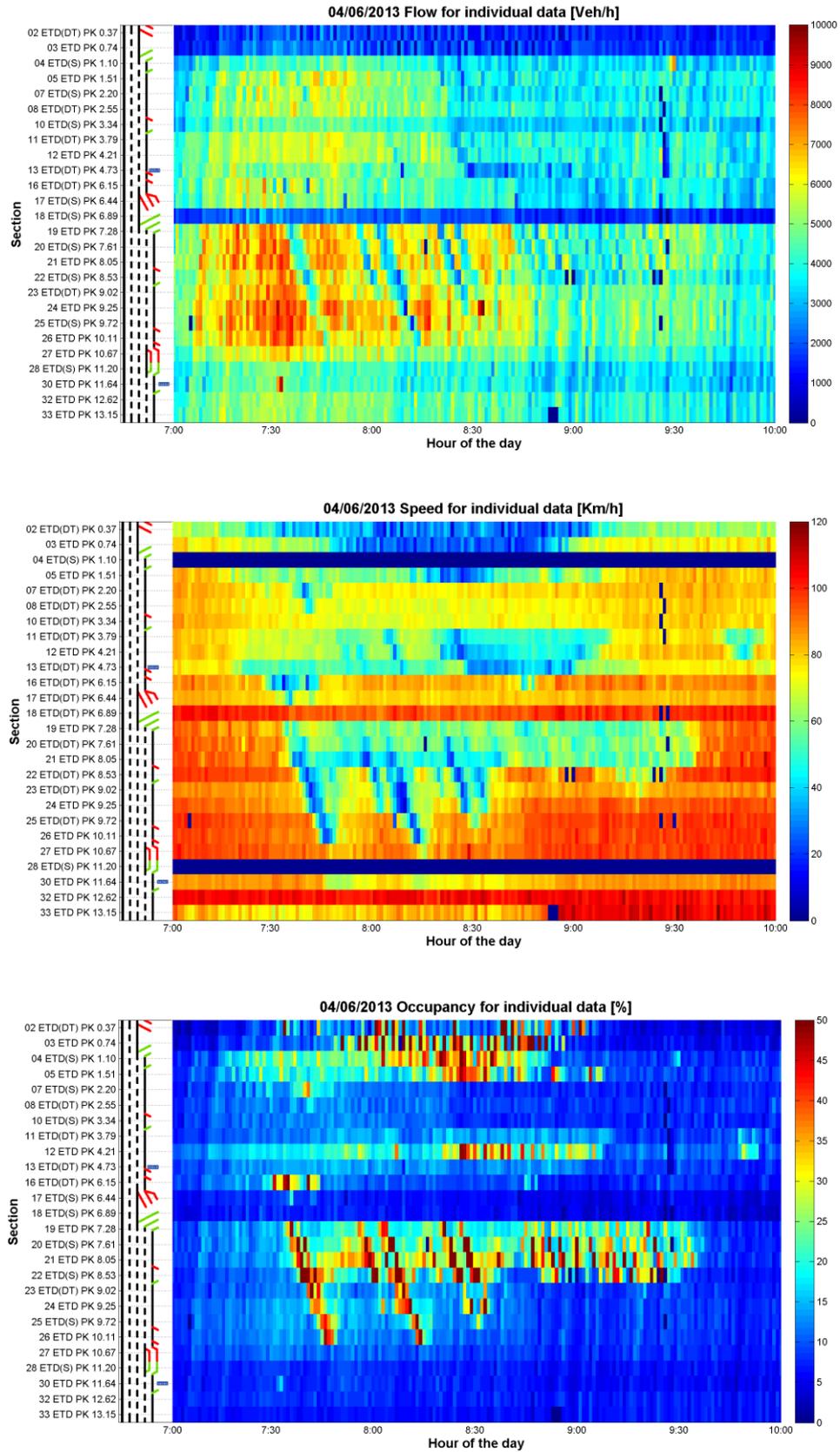


FIGURE 15 Contour plots for raw data where is available, otherwise is minute aggregated data (Data obtained between 7:00 and 10:00am on Tuesday June 4th, 2013, inbound direction).

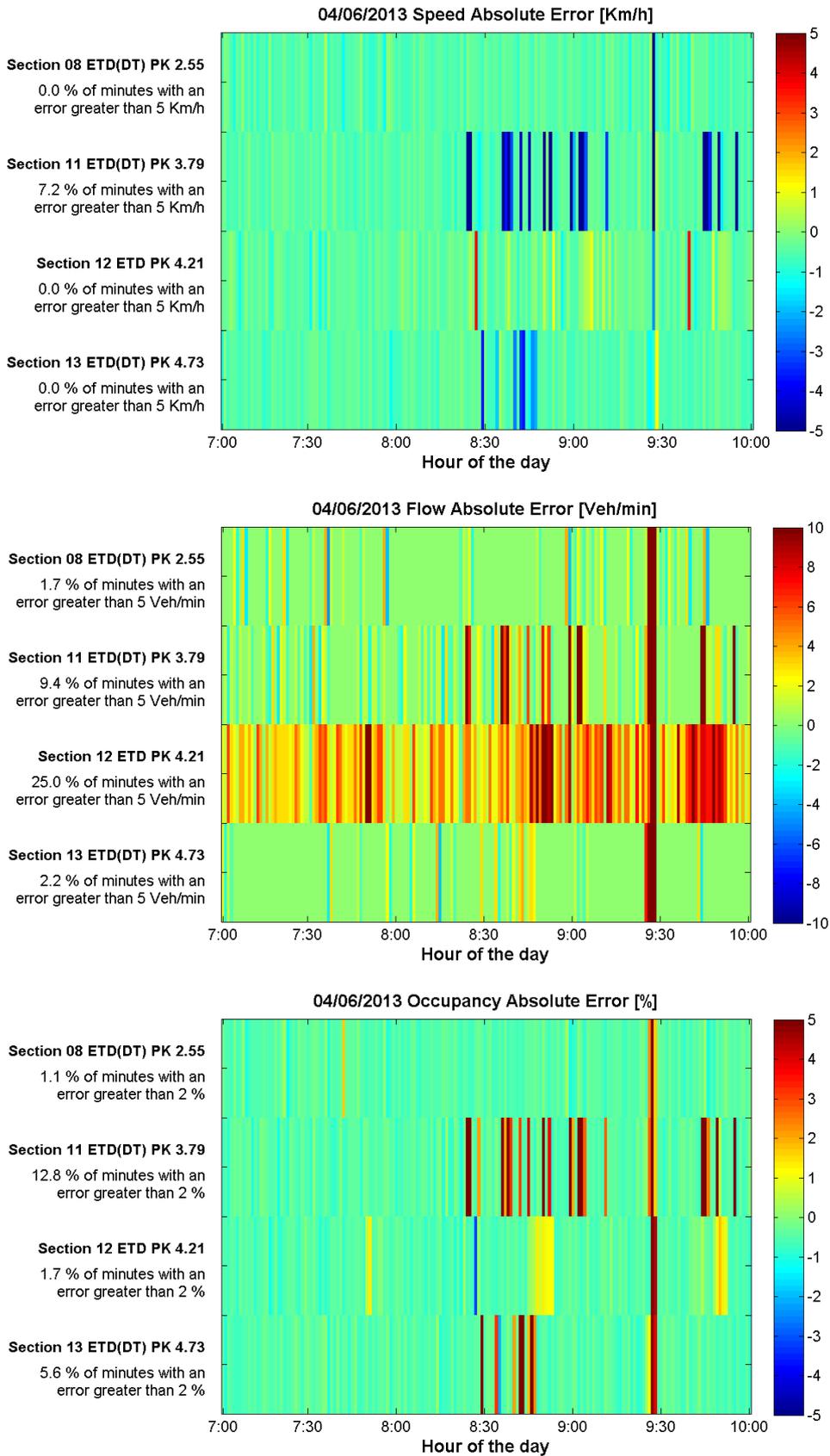


FIGURE 16 Contour plots for error between raw data and minute aggregated data. (Data obtained between 7:00 and 10:00am on Tuesday June 4th, 2013, inbound direction).

TABLE 8 Individual vehicle detection (raw data) using traffic detectors: Quality of measurements

Detector	13 (DT)		12 (Loop)		11 (DT)		8 (DT)	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Day#1	2,2%	-1.02%	25,0%	-5.59%	9,4%	-2.96%	1,7%	-0.89%
Day#5	4,4 %	-0.08%	20,6 %	-4.80%	3,9 %	-1.21%	2,2 %	-0.34%
Day#6	2,2%	-0.35%	21,1%	-4.91%	3,9%	-0.88%	2,2%	-0.70%
Day#7	0,0 %	-0.22%	22,2%	-4.91%	7,2%	-1.35%	0,0%	-0.01%
Detector	30 (DT)		27 (Loop)		21 (Loop)		19 (Loop)	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
Day#2	3,3%	-1.85%	28,3%	-5.42%	21,7%	-4.40%	12,8 %	-3.19%
Day#3	7,2%	-2.29%	30,0%	-5.40%	21,7%	-4.62%	35,0%	-5.12%
Day#4	8,9%	-2.45%	33,9%	-5.93%	22,2%	-4.64%	28,9%	-5.44%

Note: (1) % of minutes with an error > 5 veh/min. (2) Total % of vehicles lost. Minute aggregations are assumed correct

6.2.6 Per lane data overview

At this point, the reader has a detailed idea about the traffic on the freeway, but only on the sections. Therefore, what is happening between the different lanes is still unknown. In addition, some small but possible measurement errors in some lane can be overlooked due to them becoming imperceptible when aggregated.

One option would be to make a series of contour plots such as the section ones, but using lane data. Nevertheless, the result would be too many CPs, and they would not be easy to read. So, after zooming into the lanes it is time to zoom out to the previous corridor view; this time with lane averages instead of section averages.

In the flow plot, it can clearly be seen that the outermost freeway lanes (4 or 3) are the ones with major flow changes throughout the space. See as S1 and E2 have a huge effect on the lane 4 flow. Also, lane 3 is the one with the biggest flow changes, when S11 and E 12 were reached. Major exits like S7, E8 or S14 also produce a big change, but this information is not new, as it could already be seen in the section plots.

As expected, lane 1 is the fastest one. Yet a strange thing happened for both day#4 and day#7 on speed enforcement device sections. These days free speed was clearly 10 Km/h or more higher than the speed limit. The causes for this fact remain unknown. Also, on day#4, speeds on lane 4 and section 30 ETD are the higher ones. There are

two reasons that may explain this behavior. In this lane, there is no enforcement, and the exit is really near, this way drivers can feel as if the new limits do not apply on them. See Figure 18.

About the congestion related to S7, it is possible to see how the occupancy increase is mainly on lanes 3 and 4, while 1 and 2 keep it low. It happens during all the days of the experiment. This proves that this bottleneck is triggered by the beltway, not by the B-23.

After looking at the previous plot, one has the feeling that some important information is still missing. Yet with the option of a CP for each lane ruled out, another option has to be considered. This is making a series of speed CP, one every 15 minutes. It is like a photograph of the freeway every 15 minutes. It is easy to read and retains the main information. See Figure 20.

Viewing this series of contour plots, it can be seen that the congestion before the Barcelona coast beltway connection happens between 7:45 a.m. and 9:15 a.m. Also, it mainly affects lanes 3 and 4, while speeds in lanes 1 and 2 are reduced to a much lesser extent, as the lane time average occupancy plot have shown. Nothing new appears, but this confirms what less detailed plots showed.

The result is a very interesting chart, which simply but effectively shows the evolution of the freeway through the space, time and lanes.

The next logical stage is a display of the lane changing maneuver data, which is the most detailed data of the experiment. These data are intended to be the basis of an analysis of how a micro-variable such as lane changes, affects or is affected by other macro-variables. A first approach is made in the next section.

At first glance, it can be seen that the higher the divergences are between lanes (occupancy, speed or flow) more lane changes occur. For example, the camera 2305 frames just where S11 is placed. In this point, there are very big speed differences between lanes, leading to more lane changes.

An observant reader may realize that camera 2305 is the one with the biggest length of measurement (Table 11), so the bigger count could be explained because of bigger measurement length and not by more lane change activity. To give an objective proof that in fact there is more lane change activity, Table 9 is made. Firstly, an average of lane changes for each camera is calculated. Finally, and knowing the measurement length for each camera, it is as simple as dividing the average counting by the camera length. Then, an average lane changing per meter value is achieved for each camera. The two cameras with higher values are cameras 2305 and 2310. It is also noticeable that camera 2310 is framing between 23 ETD and 22 ETD, where the occupancy of lanes 1 and 2 starts to rapidly increase.

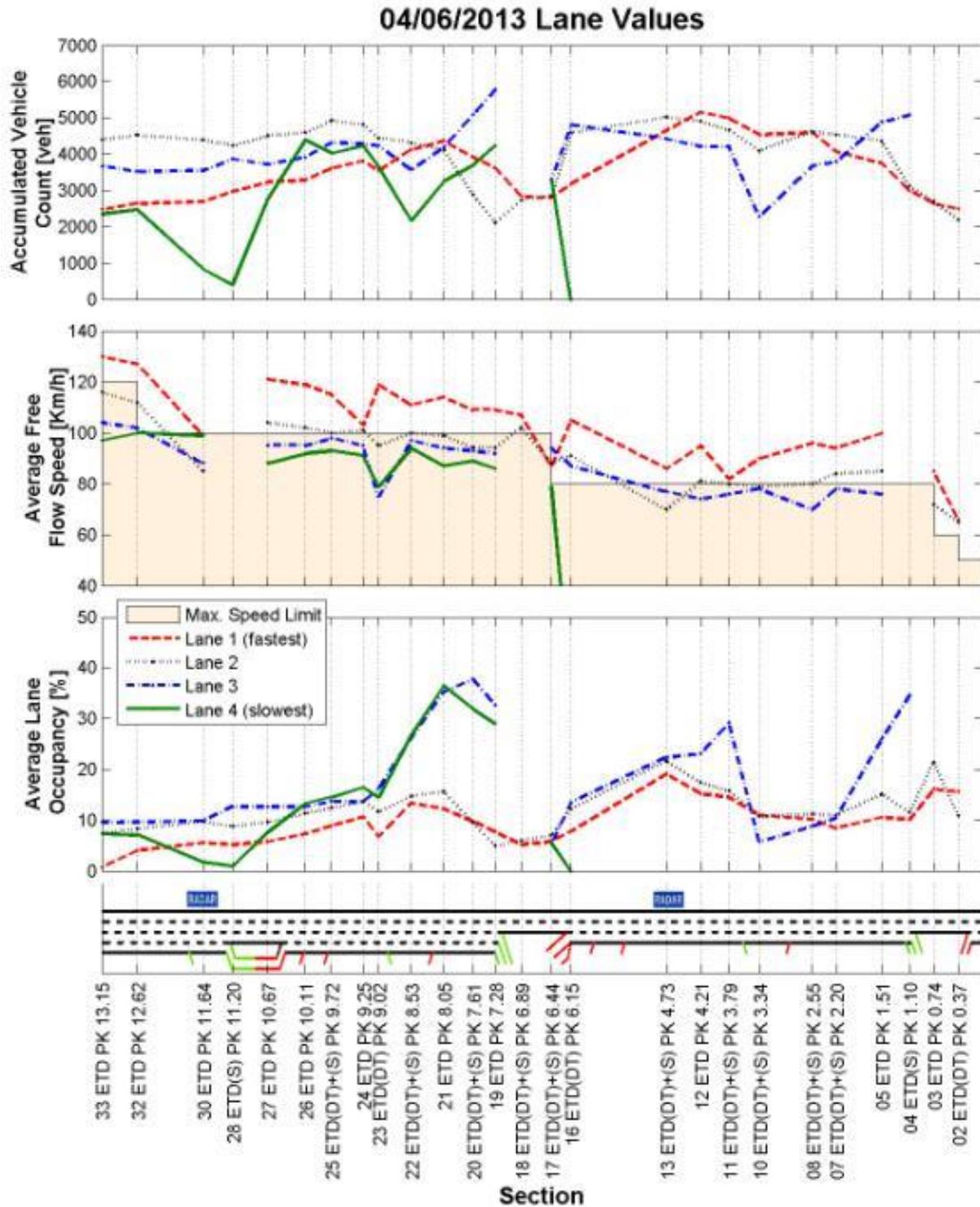
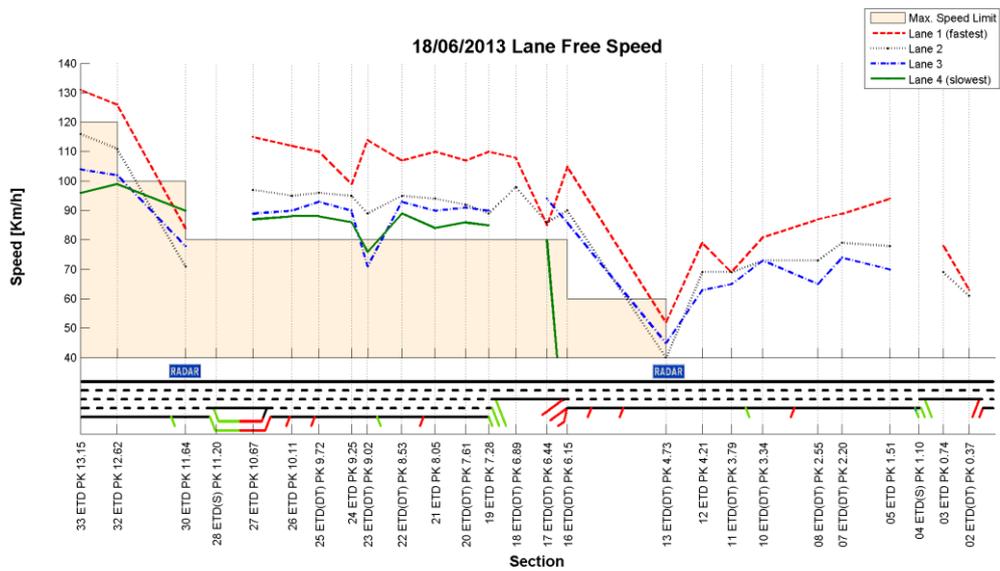
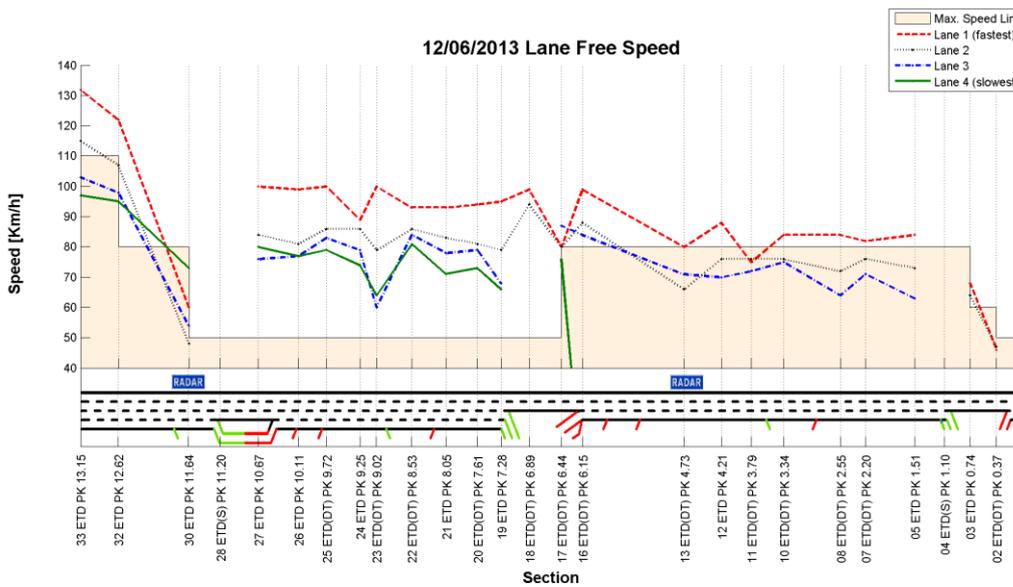


FIGURE 17 Per lane values for morning rush. a) Cumulative traffic demand. b) Free flow speed. c) Average occupancy. (Data obtained between 7:00 and 10:00am on Tuesday June 4th, 2013, inbound direction).



a)



b)

FIGURE 18 Different real lane free speeds in different speed limits scenarios. a) Day#4, outbound speed limit set at 50 Km/h (Data obtained between 7:00 and 10:00am on Wednesday June 12th, 2013, inbound direction). b) Day#7, inbound speed limit set at 40 Km/h (Data obtained between 7:00 and 10:00am on Tuesday June 18th, 2013, inbound direction).

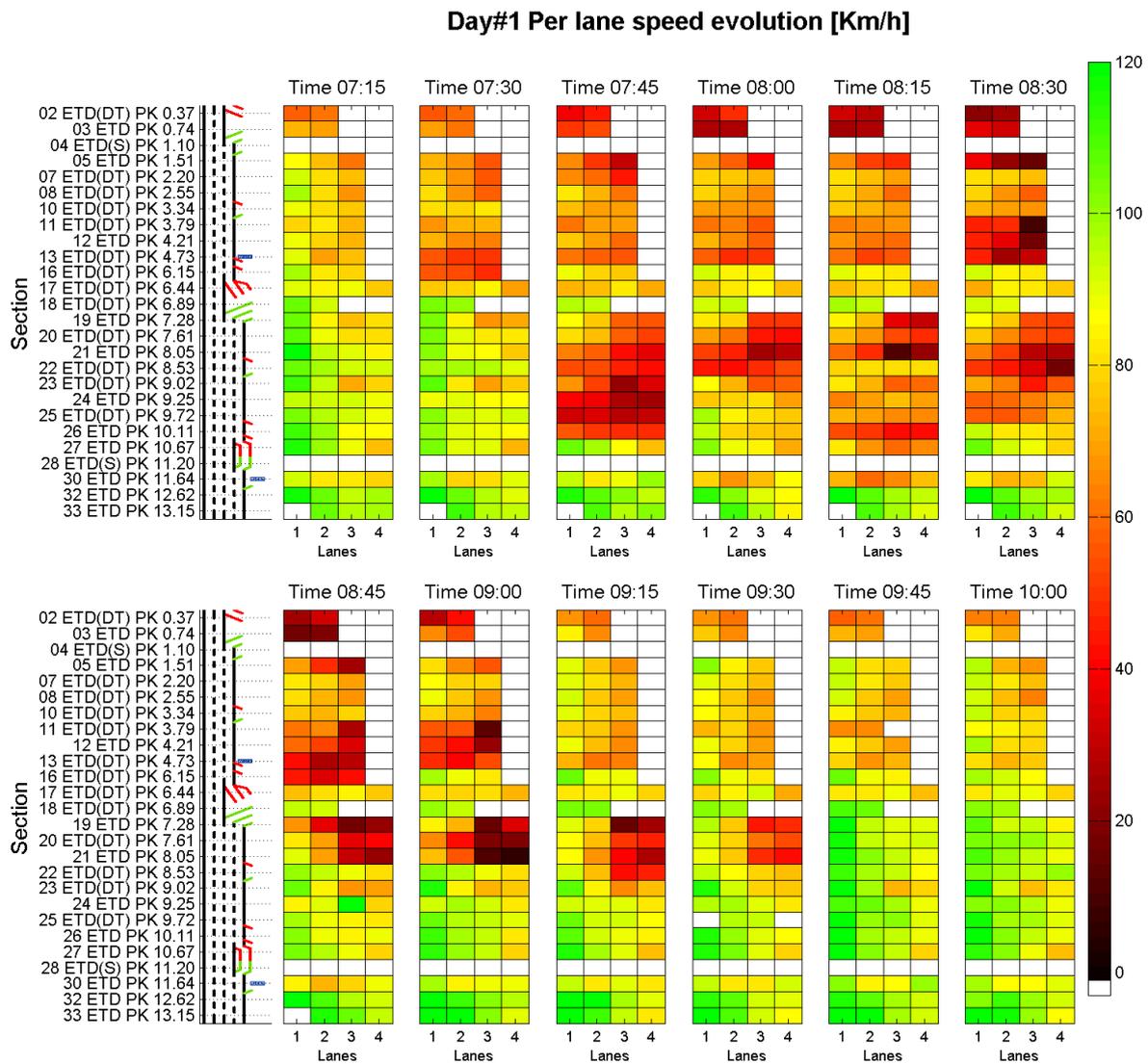


FIGURE 19 Per lane speed contour plot (Data obtained between 7:00 and 10:00am on Tuesday June 4th, 2013, inbound direction).

TABLE 9 Average lane changes per meter

Camera	2306	2305	2304	2312	2310	2309
Average lane changes per day	382	1211	264	599	588	146
Length of the measurement	115	260	90	260	120	70
Average lane changes per meter and day	3,32	4,66	2,93	2,30	4,90	2,09

TABLE 10 Total lane change maneuvers during the morning rush

TV Camera	2306			2305			2304		
	Total # lane changes			Total # lane changes			Total # lane changes		
	% slow-mid	% mid-fast		% slow-mid	% mid-fast		% slow-mid	% mid-fast	
Day#1	447			1644			223		
	62.6%	37.4%		53.7%	46.3%		65.5%	34.5%	
Day#5	266			967			289		
	60.9%	39.1%		46.5%	53.5%		47.4%	52.6%	
Day#6	343			1092			360		
	55.4%	44.6%		46.9%	53.1%		55.3%	44.7%	
Day#7	471			1140			184		
	62.6%	37.4%		57.2%	42.8%		53.8%	46.2%	
TV Camera	2312			2310			2309		
	Total # lane changes			Total # lane changes			Total # lane changes		
	% s-ms	% ms-mf	% mf-f	% s-ms	% ms-mf	% mf-f	% s-ms	% ms-mf	% mf-f
Day#2	434			374			130		
	61.8%	28.3%	9.9%	34.2%	34.0%	31.8%	51.5%	30.0%	18.5%
Day#3	563			607			164		
	43.2%	31.3%	25.6%	28.8%	30.1%	41.0%	41.5%	45.1%	13.4%
Day#4	800			783			144		
	43.9%	28.9%	27.3%	26.6%	35.6%	37.8%	41.0%	43.8%	15.3%

6.1.7 DSL

Finally, some contour plots were done which may be redundant, since the speed limits have appeared previously in other plots. Even though, they are still useful because they can be used to verify that actually the limits were those which were expected. However, it is interesting to see how in day#1, the SCT dynamic speed limit algorithm worked. See Figure 20.

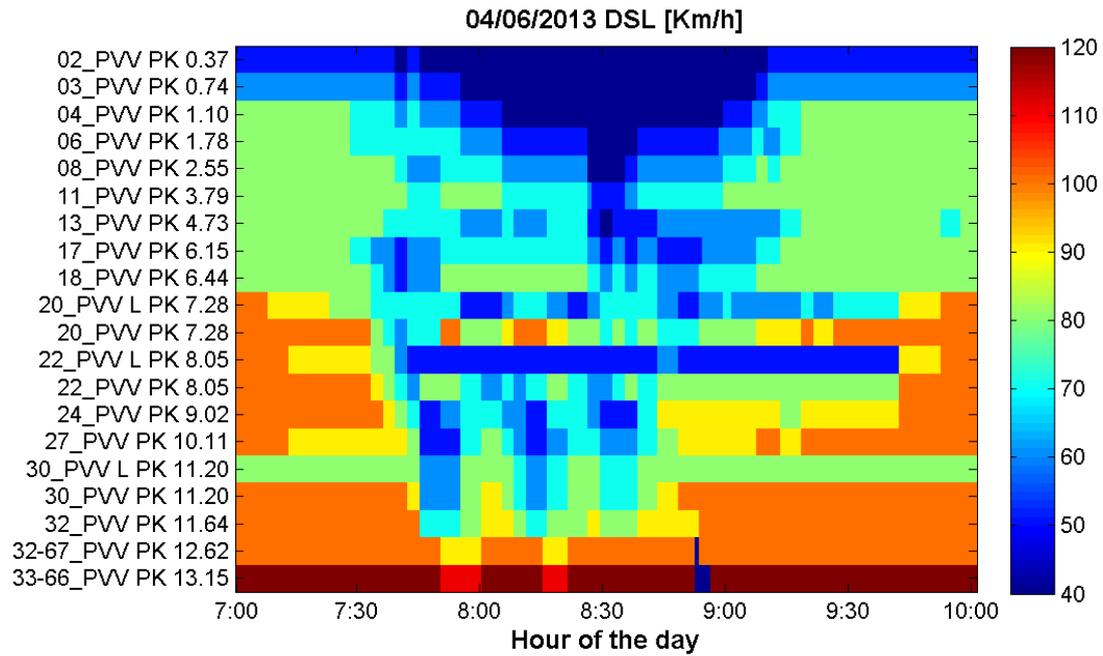
6.1.8 Experiment end

After seeing Figures 10 to 20, it is possible to conclude that the goal of including all the rush hour was accomplished, and the experiment was concluded.

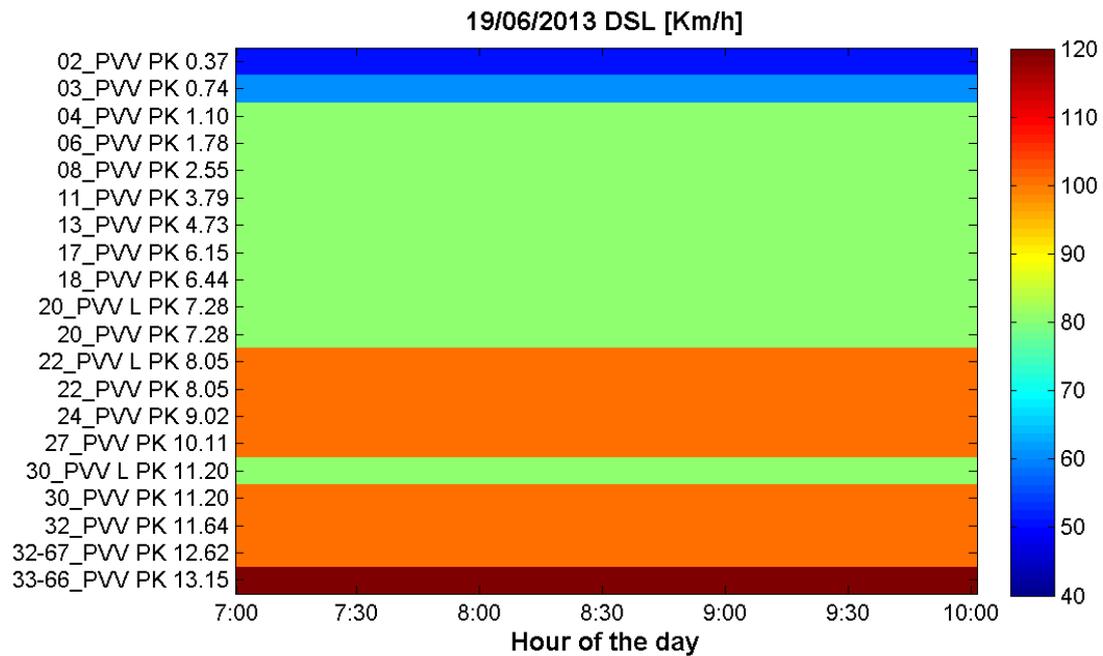
The complete database can be found at Soriguera, F. and M. Sala. (2013). B23 Dynamic Speed Limit Database [1]. Available online soon.

TABLE 11 Lines considered for lane changing counting

Camera framing with lane change epoch lines		Length	Camera framing with lane change epoch lines		Length
Cam 2304		90 m	Cam 2309		70 m 65 m for lanes 1-2
Cam 2305		260 m	Cam 2310		120 m
Cam 2306		115 m	Cam 2312		260 m 250 m for lanes 1-2



a)



b)

FIGURE 20 Dynamic Speed limits for each DSL gantry and minute. a) Data with SCT algorithm working (Data obtained between 7:00 and 10:00 am on Tuesday June 4th, 2013, inbound direction). b) Data for an experiment day with fixed speed limits (Data obtained between 7:00 and 10:00 am on Wednesday June 19th, 2013, inbound direction).

7 DATA ANALYSIS

All the analysis done until now was made in order to check the data, its reliability and to understand the traffic behavior in the freeway. While this data check was done, some realizations of particular behaviors in different scenarios happened.

7.1 RELATION BETWEEN LANE CHANGES, OCCUPANCY AND FLOW

The first one was while the lane changes counting from the epochs were done. The impression was that the denser the traffic was, the more lane changes the cars did, until it was too dense to allow the lane change, near the stop. For instance, the camera 2305 that is much more congested due to the bottleneck that appears at exit S11 has much more changes than the camera 2304 that is placed only 1 kilometer apart.

In order to give a more conclusive and objective proof of this fact, a graphic for camera and day is given, where there is a transformed T-curve, N-curve and L-curve (lane change curve). Although further research is needed, this only pretends to show an interesting path to follow with this empirical data and proof that the realization actually is supported by objective data not for all cameras and days, but for the majority.

The subtracted background flow is equal for each plot and its value is a 95% of the average. Maybe other values could result in a better graphic. However, the only purpose was to make a visualization of this phenomenon.

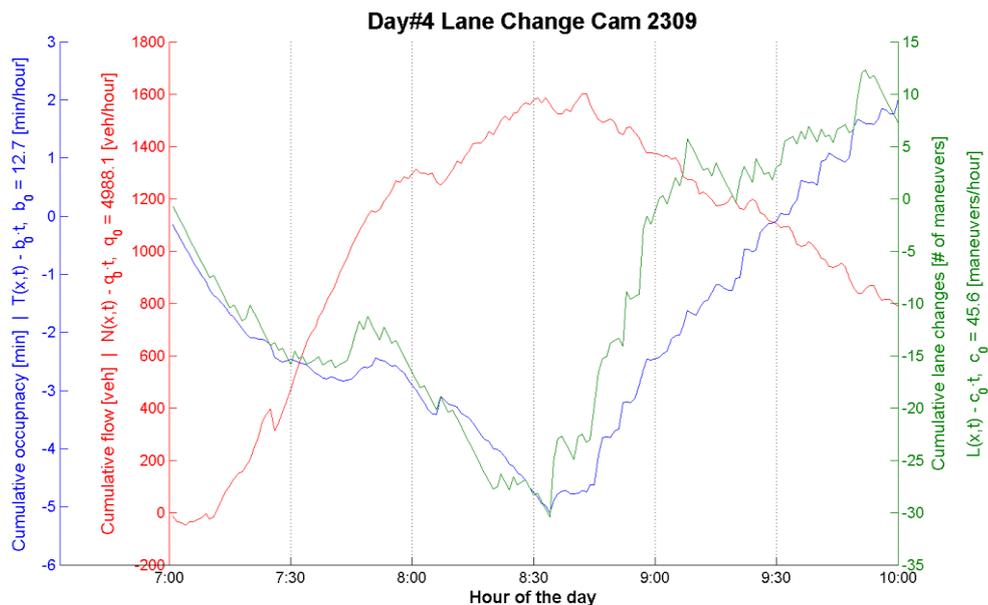


FIGURE 21 Oblique cumulative count (N), occupancy (T) and lane change (L) curves. Note 1) Data is obtained from camera 2309 and detector 20 ETD (S) on wed. 5th May 2013 (Day#4). 2) Oblique cumulative curves imply the subtraction of background values in order to facilitate the interpretation of the plot [3].

7.2 SPEED LIMITS COMPLIANCE

During the experiment everyone involved on it had the impression of general speeding happening, especially in low speed limit scenarios, with the only exceptions of the radar sections. The impression was not only from the data, but also from some people that actually drove through the B-23 inbound while the experiment took place.

So with the aim of having an objective value that helps determine if it happens or not and by how much, three contour plots were constructed assuming that the main factors that affect the real freeway speed in DSL conditions are:

- The kind of section, and there are 3 types in B-23.
 - Section with detector and any speed limit signal.
 - Section with detector and speed limit signal.
 - Section with detector, speed limit signal and speed enforcement device.
- The Speed limit itself
- The density of the traffic.

Grouping all data available by: kind of sections, density range and speed limit; a big amount of data with similar traffic conditions is available. For all data in every type of traffic condition the following calculus can be done. Note that V_L is the speed limit and V is minute average measured speed.

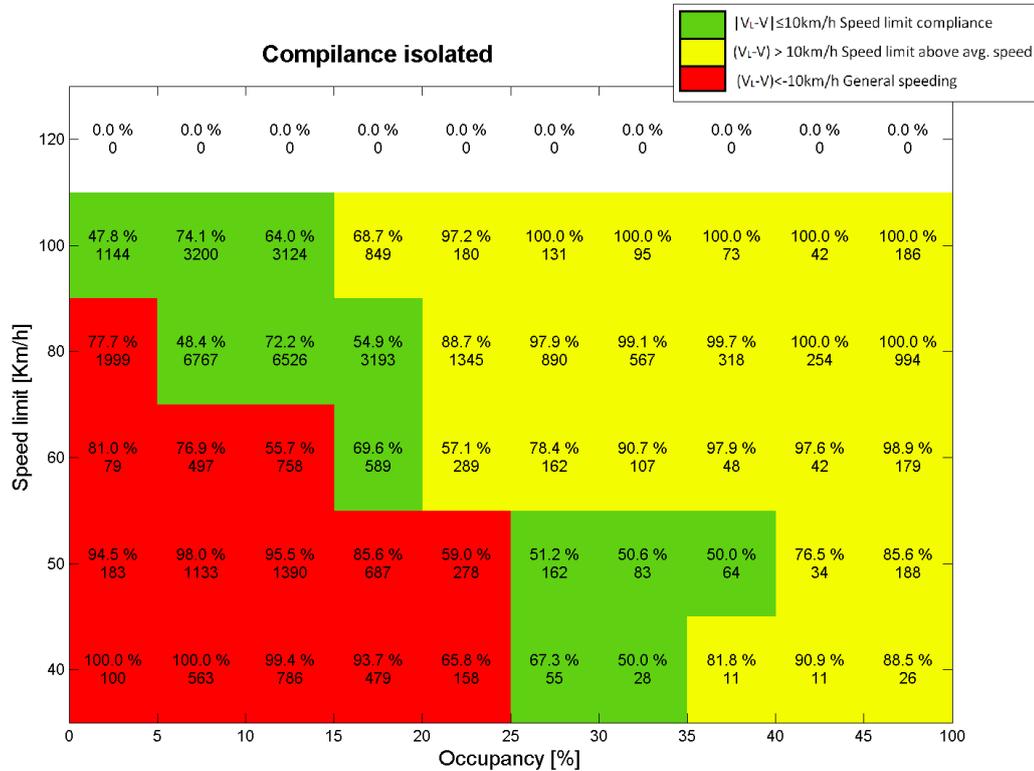
- General speeding $(V_L - V) < -10 \text{ Km/h}$
- Speed limit compliance $|V_L - V| \leq 10 \text{ Km/h}$
- Speed limit above average speed $(V_L - V) > 10 \text{ Km/h}$

In other words, firstly the data for every minute in each lane is labeled with its occupancy, speed limit, the kind of section and with one of the three compliance scenarios. Secondly, the data with similar occupancy, speed limit and kind of section was grouped together. Therefore, for occupancy the groups are: 0 % to 5 %, 5% to 10 % and so on. This is similar for the speed limits: 40 Km/h, 50 Km/h, etc. Thus in each group there is a different number of data available. The absolute number that appears in each cell of the CP is the amount of data per group.

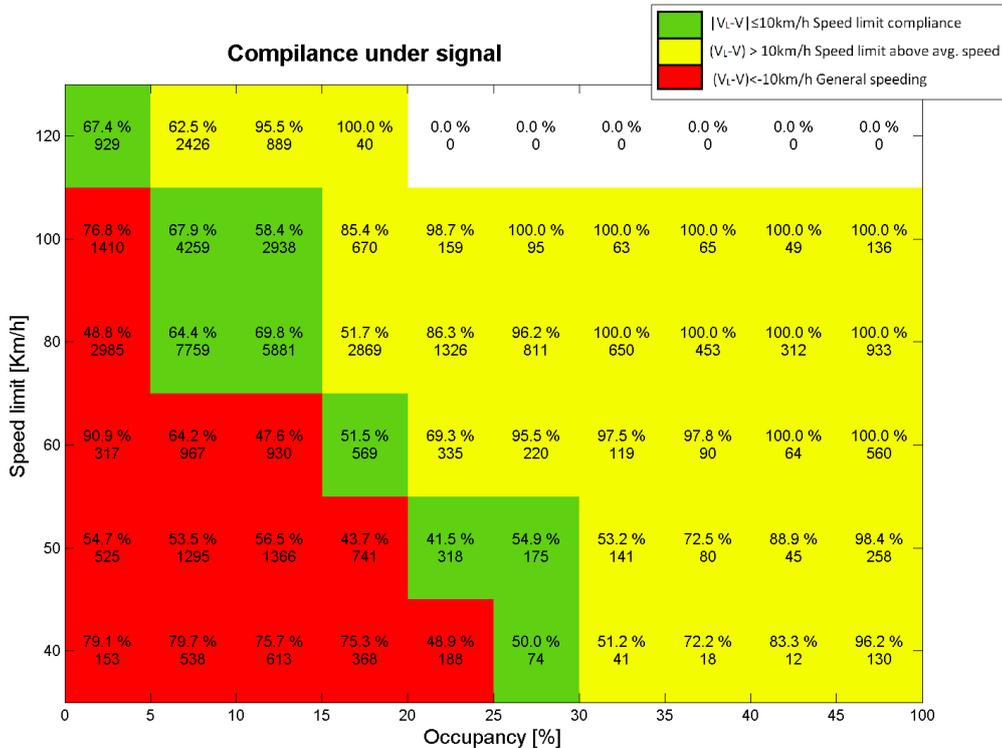
Up to this point, there are only three categories of data in every cell: speeding, speed limit compliance and speed limit above average speed. One of the three categories has to prevail over the other two; this one is what determines the color of each cell. The percentage number is the percentage that the prevalent scenario has over the total.

A simple example is, in one group there is a 100 data, 45 of them correspond to the speeding scenario, 35 to the compliance scenario, and the last 20 to the speed limit above average speed. Hence, the cell for this group will be red, as speeding is the prevalent value. The percentage will be 45 %, and the absolute number will be 100.

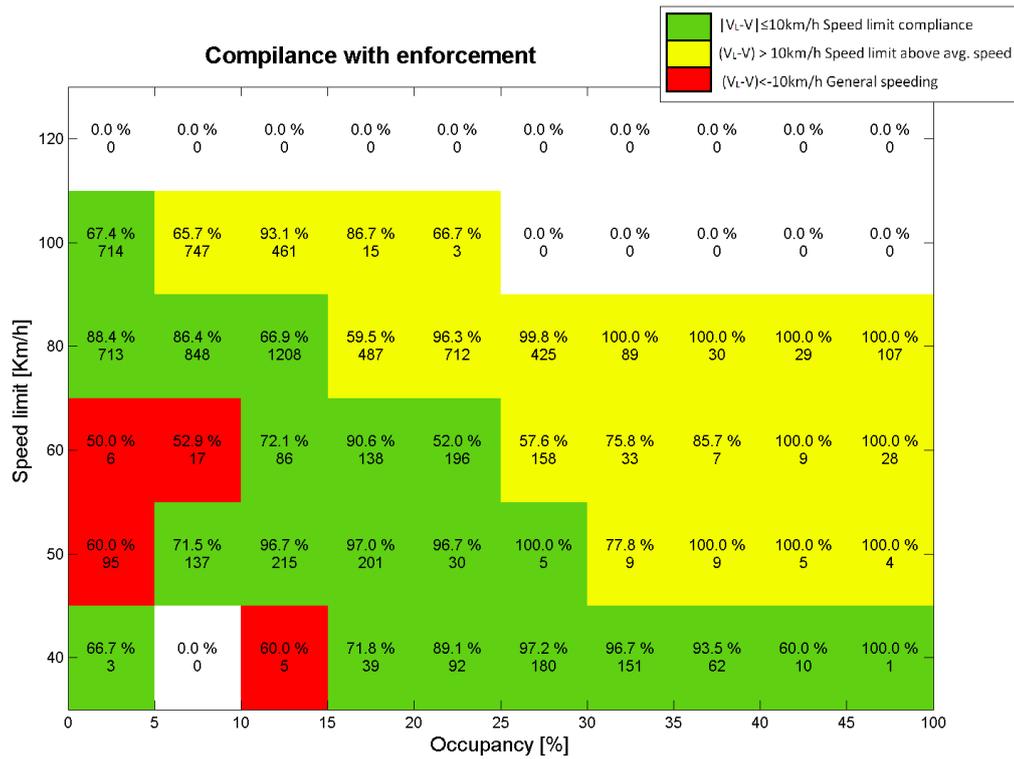
Looking at figure 22, it is clear that for low traffic density and low speed limits speeding is generalized, except for those sections with speed enforcement devices. For high occupancy rates the speed limits are ineffective as they are over the freeway average speed.



a)



b)



c)

FIGURE 22 Speed limit compliance. In each cell are the percentage of the majority and the total amount of data in each group. a) Isolated detector. b) Detector under speed limit signal. c) Detector with speed enforcement device.

8 CONCLUSIONS

After doing all this research work, from the layout construction, continuing with the experiment design, data treatment and finishing with the first data analysis, some conclusions can be done.

8.1 TRAFFIC BEHAVIOR

Traffic in the 7 days of the experiment was similar in general, but there were remarkable small differences.

As seen on 6.2, the Barcelona city entrance has been a more restrictive bottleneck some days compared to others, causing bigger delays. What causes this is not known because it happened outside the experiment site, so there is no available data. In future experiments, it is desirable to collect data downstream of the experiment site because as congestion shock waves go upstream, they affect the experiment. The same applies for the bottleneck that appears at S7, the connection to the coastal Barcelona beltway.

Traffic regulations have a low compliance. There is a general speeding, as seen in point 7.3. Even more, at the camera 2305 it is not uncommon to see drivers driving between lanes 2 and 3. Some actions have to be taken to make drivers more aware of the importance of traffic regulations fulfilment. To set up more speed enforcement devices in critical sections would be a first solution to this problem.

In contrast to the low speed limit compliance, there are speed enforcement device sections where the compliance level was high, although it was not 100%. As a consequence of this fact, traffic clearly changes its behavior downstream from these sections with the different speed limits scenarios. Traffic is more homogenous and stable with less stop and go the days that lower speed limits were applied.

Regarding lane changes, after a detailed look at all the figures made for the database, it is possible to conclude that, in general terms the higher the occupancy is (until it is too high) the more lane changes are done. Also, the bigger the differences between the lanes are on speed, occupancy or flow, the more lane changes are done. Some of the most relevant figures that prove this fact are shown in points 6.2 and 7.1.

8.2 FURTHER LINES

More research can be done with this data. The work done in the present master thesis gives a clear but still not irrefutable proof of the supposed benefits of DSL, such as the traffic homogenization and reduction of traffic congestion. In order to definitely proof that the traffic homogenization happens, it is recommended to do a very detailed

analysis, and to focus on raw data on speed enforcement sections. These future studies could be the irrefutable proof of the claimed benefits of DSL systems.

Given all the exposed previously, a strong recommendation is made to focus on the traffic data downstream from an enforcement device, when working on DSL effects. Otherwise, the DSL effects can be too subtle to differentiate from the natural variations of traffic. Note that the raw detectors are the ones set on the speed enforcement devices and downstream of these.

8.3 EXPERIMENT DESIGN CONCLUSIONS

Once all the work is done (planning and doing the experiment and the first data treatment and analysis), and given the gained experience, some basic recommendations can be done.

It is extremely recommended to have the goals very clear from the very beginning. Thus, the first decisions are: where, when, why and how to do it. Specifically, it has to be clear what the data is going to be used for, determining which data is necessary to collect and how it has to be processed and stored.

Once this is clear, it is the moment to design the experiment and to do the final agreements with the traffic administration. Probably, some changes to the previous planning may have to be done. It is better to have this clear from the very beginning; otherwise much extra work will have to be done.

Also, for future empirical data collecting from freeways with DSL, it is recommended to use all the means available in order to achieve the maximum fulfillment of the speed limits.

More recommendations about experiment designing can be found along this document and in appendix A1.

9 REFERENCES

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APPENDIX A1: INCIDENCES AND SUGGESTIONS FOR THE TRAFFIC MANAGEMENT ADMINISTRATION (SCT) AND TRAFFIC MANAGEMENT CENTER TMC

1 PROBLEMS DESIGNING THE EXPERIMENT

This experiment about the effects of the DSL in the Barcelona inbound freeway had to be in collaboration with the SCT, because they are the administration in charge of the freeway. So, they have all the information of the freeway, the loop detectors, the cameras, LPRs, and, even more important, they decide about the actions on the freeway, such as the speed limit in every moment.

Due to these reasons, a total agreement about the terms of the experiments with the SCT is essential. Because of the very different characteristics of the experiment related to a regular operational day in SCT freeways, some things were difficult to reach an agreement. The bigger problem was the 40 Km/h speed limit, firstly looked as impossible to set. But after some days and a calmed analysis, a solution between the interests of both SCT and UPC was exposed. It consisted in dividing the corridor in two parts.

One part was the 6 kilometers closer to Barcelona, and the other part was the rest of the corridor. The SCT solution was, on one day, to set the 40 km/h speed limit in the inner part while the outer part remained with the 80 km/h limit. Then, on another day, the inner part would be set at 80 km/h while the outer part of the corridor would be limited at 50 km/h.

Their reason to not set the 40 Km/h limit, as suggested by the UPC, was the unacceptable delay produced in the drivers. It would be 8 minutes on rush hour, assuming that all the vehicles were able to reach Barcelona at the maximum speed limit during the entire freeway. So, in the likely event of congestion, the delay produced by the lower speed limit would be lower.

Anyway, their concern is understandable because back in 2007, when the Catalan government took the decision to cut down the speed limits to 80 Km/h from 100 Km/h or 120 Km/h, depending on the freeway, with the aim to reduce air pollution, it generated a lot of controversy and most of the society and media were against these new limits. Since then, everything related to the freeway speed limits is a very sensitive issue.

Secondly, the team at UPC assumed that they could have the one minute aggregated data plus the individual vehicle data for each detector. But for some reason, apparently the outdated capacity of the TMC designed some years ago, only 4

detectors could be recorded this way; it could be any of them, but only 4 in number. There were no problems for getting the aggregated data.

Thirdly, talking about the video recording, an important thing happened. For the experiment, it was expected to have recorded all the cameras placed through the experiment site. But this was impossible with the settings of the TMC at the present time, because to record high resolution video, a special computer for each camera is required. Thus, to record with all the 13 cameras on the corridor, 13 computers are needed. The problem is there are only 7 computers able to do this, and a minimum of 3 are required for traffic surveillance, so only 4 cameras could be recorded. Whereas the option was having more computers, a total of 16 (3+13), they had no short-term expectations of having any more.

In addition to the camera issues, there was another problem. In spite the fact that the software at TMC allows saving camera prepositions. This means a few minutes before the experiment takes place the cameras can be framed automatically as it is wanted to be framed. The problem is that after some minutes, the system is unable to frame the camera properly, so manual framing had to be done every day from screenshots taken from each camera at the correct position following the chart presented at Figure 9 of the report.

In addition, another problem was the fact that most of the information about the equipment set up at the freeway was not accurate enough for a scientific experiment, especially the kilometric point information. It was specially critic when the layout was built. Therefore, to check the placement of all the equipment, Google Earth and Google Street View were used. Furthermore, some of this equipment was not working, and there was no guarantee that it was going to work for the experiment.

2 EXPERIMENT TAKES PLACE

When the experiment took place, 3 cameras were recorded, each one in a different computer, with different hardware, so in spite of the video files having the same pixels, codec, fps, etc., the video hue, contrast, brightness, sharpness and fluidity were significantly different. Besides, some incidences happened on the first day of the experiment, the framing and video quality of some cameras was not okay. Additionally, one camera had some focusing problems, the image was good enough to be used, but could be much better. So, a strong recommendation is to do an accurate revision of every single piece of equipment involved in the experiment before it takes place.

Some detectors did not work during some hours of the experiment for an unknown reason. Fortunately almost all the data was stored at some part of the detectors and could be recovered later.

Different traffic detectors types are installed at the B-23 freeway, and each one has its singularities, the detector types are:

- Simple loop detectors. ETD (S) in the present document
- Double loop detectors. ETD in the present document
- Double technology detectors (radar + infrared and laser). ETD (DT) or only DT in the present document.

Simple and double loop detectors are almost the same, the only difference is that simple cannot measure speed and double can. All of these detectors were placed long ago, so the hardware they have is not very powerful. Therefore, when loop detectors attempted to save the data for each single vehicle the data exceeded the hardware capacity and some of it (about 5%) was lost, see Table 1. Even though, this kind of detector is good at measuring occupancy times and work the same way with low dense traffic or heavy traffic.

The other type of detectors available is DT detectors. They were installed for the DSL project in order to have enough data to decide properly the future dynamic speed limits. In traffic analysis terms, the advantages of this kind of detectors are due to their novelty. So, they have a powerful hardware able to manage the data of individual vehicles much better than the older loop detectors. They can record, with a small miscounting increase, the data for each single vehicle. Moreover, they do not over count vehicles as in some cases loop detector do (detector drift).

The deficiencies that this type of traffic detectors presents are the following. Firstly, in highly dense traffic they miscount lots of vehicles due to their normal working. Secondly, the occupancy measurement of the DT technology is hypersensitive to the variations of the equipment alignment over the pavement (i.e. 20 degrees alignment is an adequate installation). This results in a poor accuracy of these measurements. So at sections with both DT and S, data from DT was used for speed, and data from S was used for vehicle count and occupancy.

3 SUGGESTIONS TO IMPROVE FUTURE EXPERIMENTS

Only after describing all these problems, deficiencies and disagreements, some suggestions for improvements can be made, either at SCT TMC or generic for any researcher interested in conducting a similar experiment.

It is very important to do the agreement with traffic administration step by step and clarifying every hardware and software available, and to not take anything for granted. So, for example in the B-23 case, from the very beginning an email had to be sent to SCT making explicit that all the cameras with high resolutions and all the traffic detectors with individual data were wanted.

TABLE 1 Consistency of total cumulative vehicle count amongst DT and ETD (S)

Detector	08 ETD		10 ETD		11 ETD		13 ETD		17 ETD	
	Abs. ⁽¹⁾	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.
Day#1	292	2,26%	-90	-0,82%	-66	-0,47%	-1851	-13,11%	146	1,19%
Day#2	341	2,62%	-111	-1,00%	-197	-1,39%	-1872	-13,09%	74	0,59%
Day#3	93	0,74%	782	7,34%	76	0,54%	-2009	-14,12%	46	0,37%
Day#4	103	0,80%	303	2,74%	224	1,57%	-2066	-14,25%	98	0,77%
Day#5	261	2,04%	-67	-0,61%	-129	-0,92%	-1628	-11,27%	150	1,22%
Day#6	80	0,62%	96	0,88%	-257	-1,82%	-2005	-13,87%	94	0,76%
Day#7	-75	-0,58%	-247	-2,25%	-276	-1,94%	-3797	-26,50%	78	0,63%
Detector	18 ETD		20 ETD		22 ETD		25 ETD			
	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.	Abs.	Rel.		
Day#1	398	7,14%	-1583	-10,14%	-471	-3,31%	-2312	-13,68%		
Day#2	418	7,39%	-1943	-12,22%	-786	-5,39%	-2284	-13,29%		
Day#3	317	5,62%	-1613	-10,12%	-472	-3,22%	-2391	-13,97%		
Day#4	513	9,02%	-1468	-9,32%	-598	-4,11%	-1902	-11,04%		
Day#5	420	7,48%	-1263	-7,92%	-347	-2,38%	-2052	-11,88%		
Day#6	492	8,83%	-92	-0,63%	-357	-2,42%	-1819	-10,53%		
Day#7	126	2,18%	-1191	-7,45%	-568	-3,87%	-1960	-11,30%		

Note: (1) Abs. Stands for the absolute difference in total accumulated vehicle count between non-intrusive detectors (DT) and single ETD inductive detectors (S); Rel. stands for the relative difference.

If video is going to be used, it is very important to do some tests of the recordings before the experiment. Thus, ensure that light condition is good enough, and the method chosen for extracting data from the video works efficiently.

Ensure that all the detectors work properly before the experiment and have enough accuracy for the wanted use. A strong recommendation is made to do a full day long test before the experiment takes place with the minimum affectation possible, so, only collecting data with the standard DSL algorithm.

3.1 Suggestions for the TMC for the B-23 freeway

Some specific suggestions are made to SCT to make the B-23 freeway a better highway lab.

About the detectors and general monitoring of the freeway, additional detectors should be placed at on-ramps and off-ramps at least to meter the entering and exit flow. One or more detectors had to be installed between 16 ETD PK 6,15 and 13 ETD PK 4,73, because a distance of 1,5 Km without any detector is too large.

Seeing that the double loop detectors are the most reliable in dense traffic, they are the most suitable. However they are expensive and outdated. So, a strong

recommendation is using MEMS traffic sensors, which work the same way as double loop do, but are smaller (like a shoe box) and wireless, so its installation and maintenance is cheaper and easier. They work with batteries that last about 2 or 3 years.

Besides, a suggestion is made to improve the hardware that takes the data and sends it to the TMC of all loop detectors, single or double, since it is desirable to have the most accurate individual data.

Even though the exact reason that makes the recording of individual data from all the detectors in the corridor impossible is not clearly known, it is strongly recommended to invest in the equipment necessary to make this happen. It is assumed that it is something at the TMC, because all the detectors can be recorded individually, but not all at the same time.

The final suggestion is improving the video display and recording system, because the deficiencies that the actual one presents are too many and too severe. Additionally, try to have some more cameras to have a better coverage of the freeway.

The new improved system has to be able to satisfy all the following requirements.

- The digital image recording has to be direct from the video camera, not like now, that the camera converts the digital signal to analogic video signal, and at the TMC the analog signal has to be re-digitalized.
- A simultaneous recording has to be available for all the cameras in at least one chosen corridor. The video recording will not take place in the video operator's station; it is going to take place in a different computer, specially built to do this function.
- About the cameras, the experiment had a video recording quality of 536x400 pixels, ignoring if this is a limitation of the cameras or the hardware at TMC. In the case that the limitation were from the cameras, an upgrade to higher qualities would have to be planned. Moreover, an improved preplacement system has to be implemented, in order to make easier the camera framing. Furthermore, the cameras have to be suitable for a digital treatment of the image.

APPENDIX A2: CONTOUR PLOTS FOR THE PREVIOUS ANALYSIS

This appendix only contains the contour plots delivered by SCT in order to do the previous analysis. As they were made by SCT, they are different from the others found in this Master thesis elaborated by the author.

The structure of the following contour plots is the following: space is on the x-axis (with the kilometric point of the detectors indicated) and time is on the y-axis (from 7:00 a.m. below to 10:59 a.m. on top). Kilometric points may differ from those on the layout. This is because real kilometric points were used in the layout and SCT kilometric points were used here.

The previous analysis was made with data from the following workdays:

- Wednesday January 23rd, 2013.
- Wednesday January 30th, 2013.
- Thursday January 31st, 2013.
- Monday February 04th, 2013.
- Tuesday February 05th, 2013.
- Wednesday February 06th, 2013.
- Thursday February 07th, 2013.

Two contour plots are presented for each day.

1. Firstly, a standard CP, speed from 0 to the maximum appeared that day.
2. Secondly, a CP where only speeds lower than 50 Km/h are plotted. Higher speeds are in grey. This second plot was made by SCT because the color scale they had used made it more difficult to distinguish between different speeds.

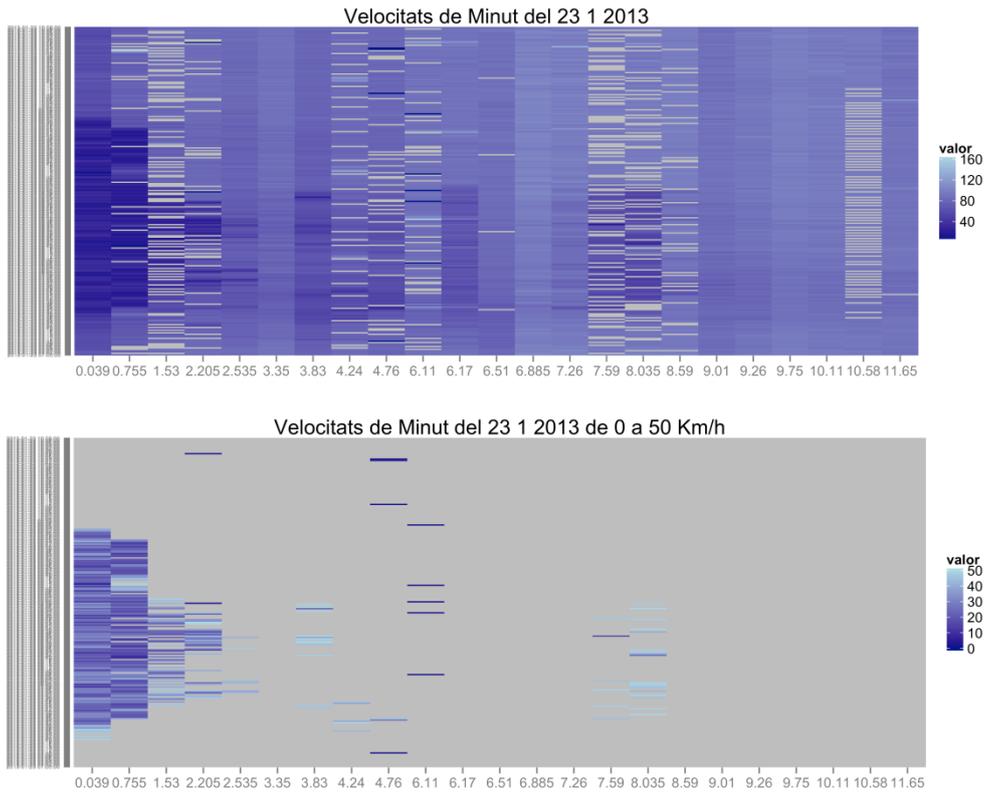


FIGURE 1 Speed contour plots for Wednesday January 23rd, 2013.

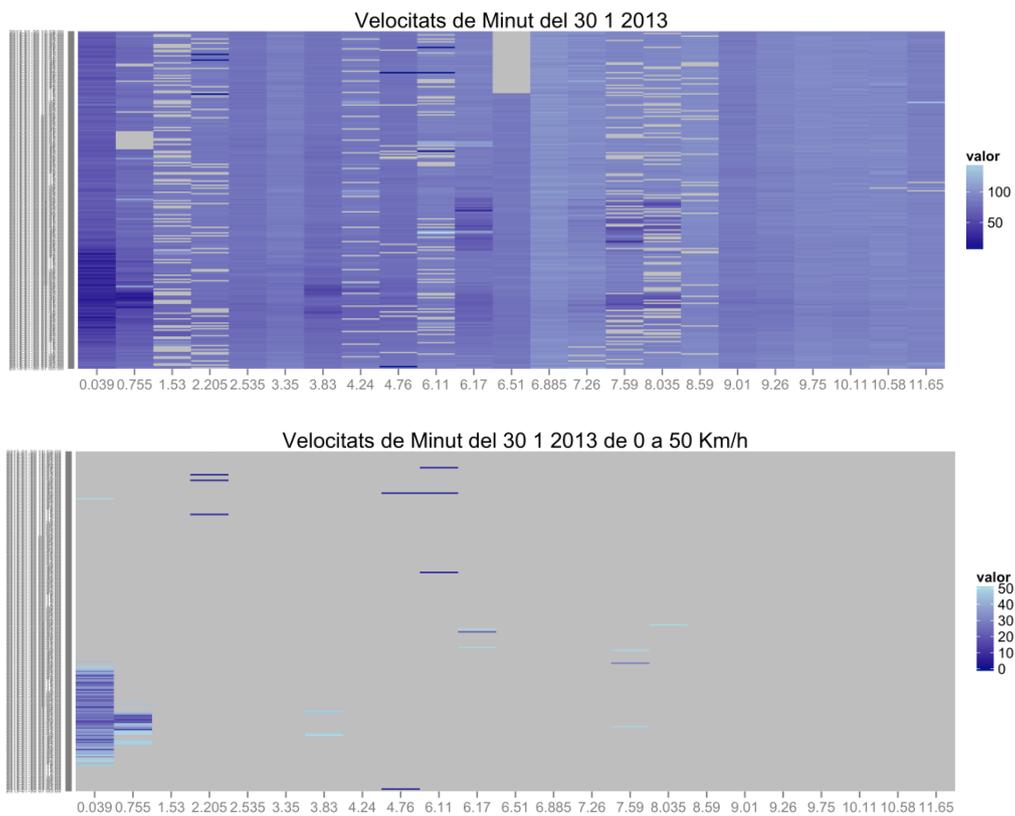


FIGURE 2 Speed contour plots for Wednesday January 30th, 2013.

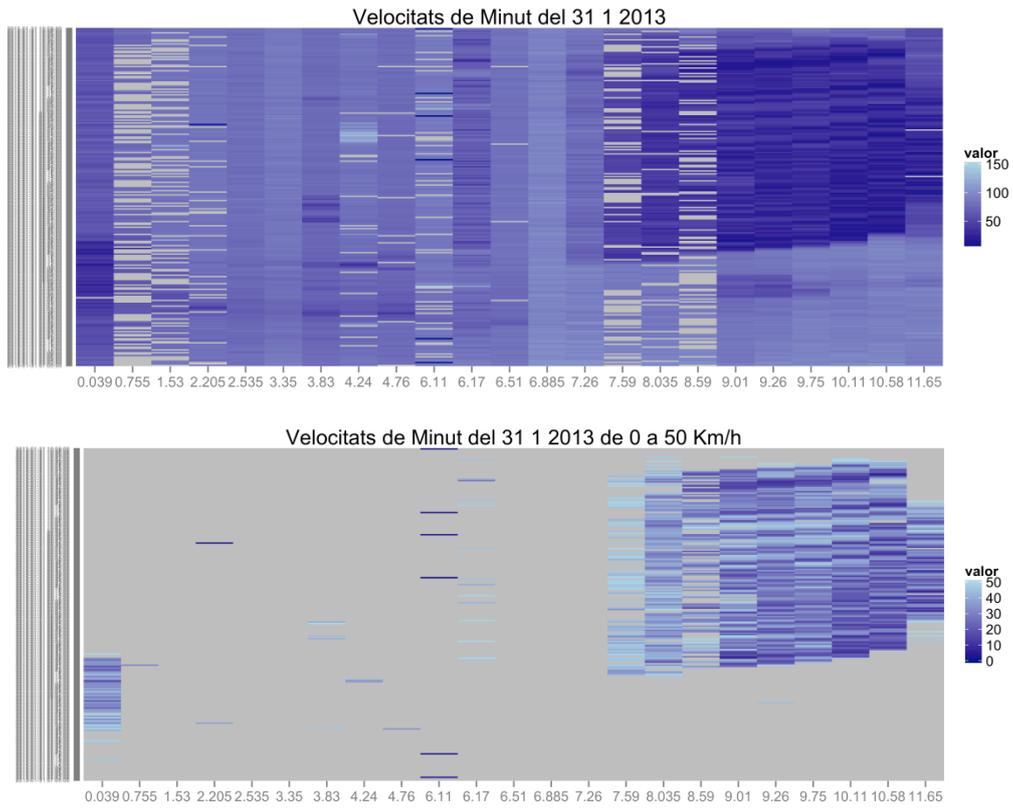


FIGURE 3 Speed contour plots for Thursday January 31st, 2013.

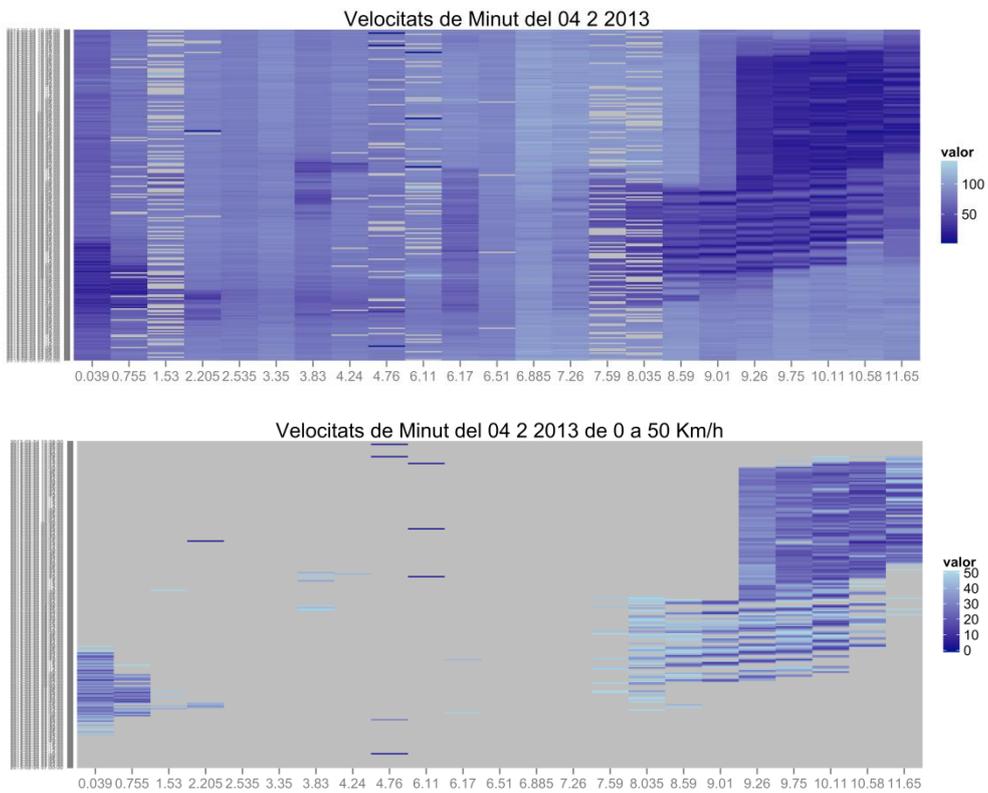


FIGURE 4 Speed contour plots for Monday February 04th, 2013.

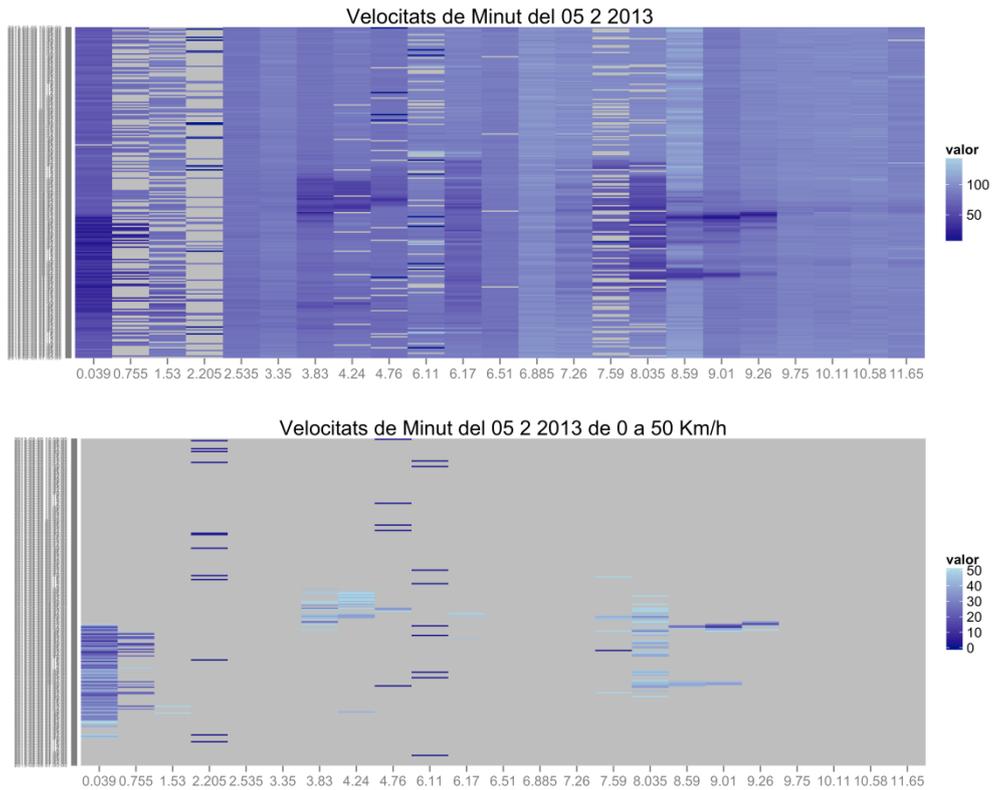


FIGURE 5 Speed contour plots for Tuesday February 05^t, 2013.

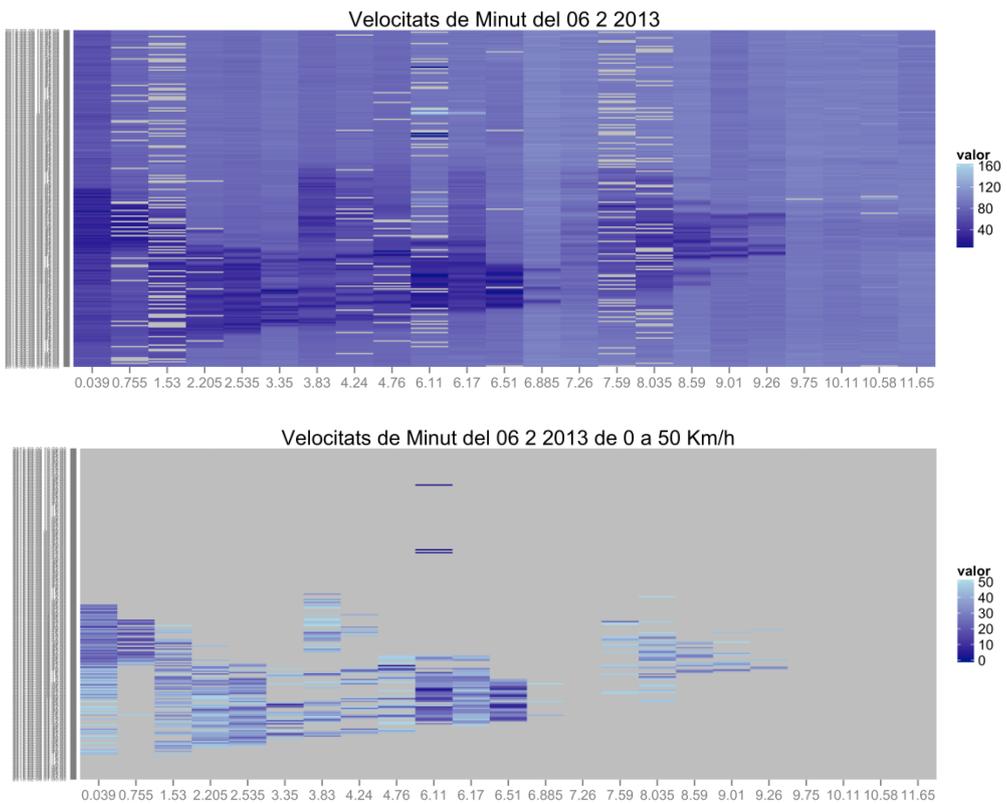


FIGURE 6 Speed contour plots for Wednesday February 06th, 2013.

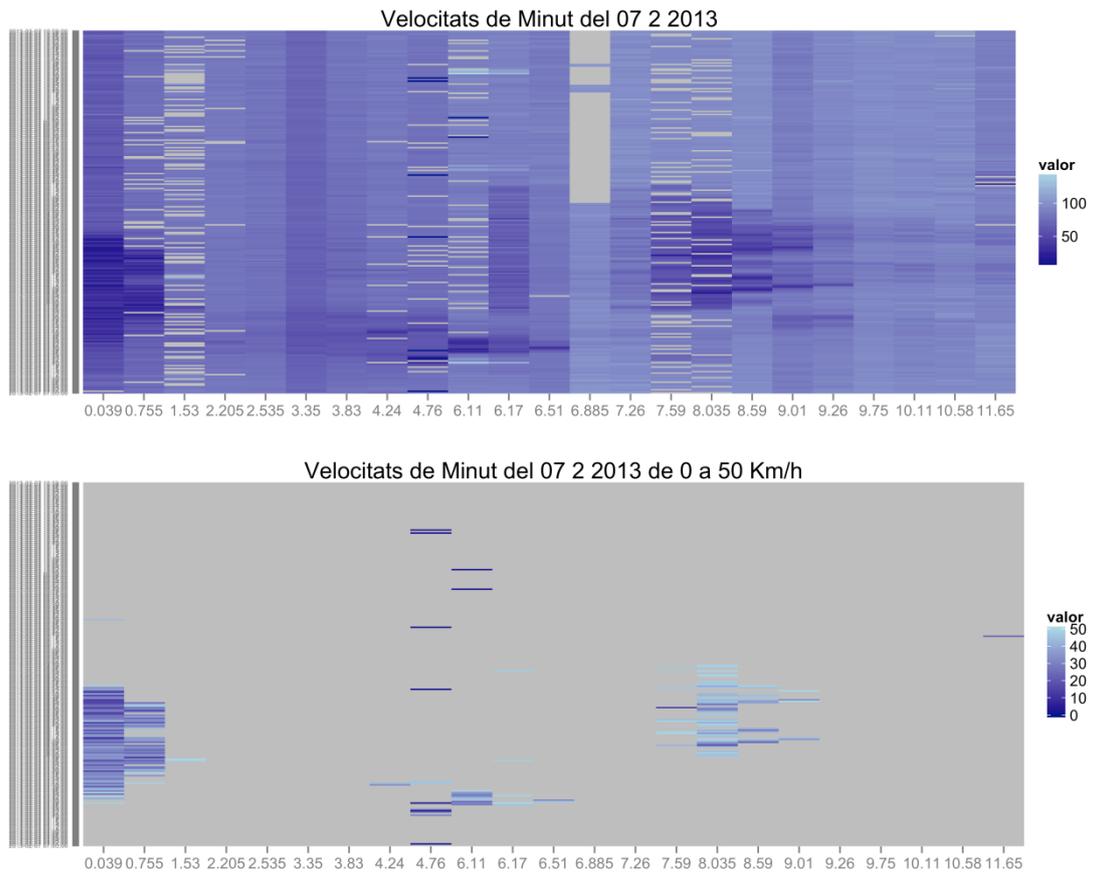


FIGURE 7 Speed contour plots for Thursday February 07th, 2013