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**Variable Speed Limit Control on Urban Highways**  
**Final Report - FPZ - ZITS - 01 - 2017**

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## **1. Introduction**

This technical report, which has the title “Variable Speed Limit on urban highways”, describes the work done during the Gabriel Melo’s internship in the Department of Intelligent Transportation Systems, Faculty of Transport and Traffic Sciences, University of Zagreb. The internship was financed by the USP Innovation Agency with the aim to study the possibilities to simulate different controllers for changing of the speed limit on urban highways.

The road network in major cities is prone to everyday recurring congestions. To solve this problem many approaches are applied, like intermodal transport, encouraging mode shift from car to public transport or non-motorized transport, building new transport infrastructure, etc. One of the approaches is the application of solutions from the domain of intelligent transportation systems (ITS) i.e. establishing various services to help the transport network users to optimally use it. A very important service from the domain of ITS is road traffic control, and it is applied to urban and rural road networks to improve its throughput, reduce congestion and vehicle emissions, improve the level of service (LoS) and reduce accidents. One special case of roads are urban highways built as bypasses around larger cities or to connect urban districts of mega cities including suburbs with the city center. They characteristic are a larger number of nearby on- and off-ramps.

On urban highways, speed limits are used on bottleneck locations i.e. on locations where congestion occurs to improve their LoS. Usually, the bottleneck locations are related to places where on- and off-ramps are located. Since the traffic demand is changing during the day, variable speed limit values are used today to change the speed limit according to the current traffic or weather situation. This concept is called Variable Speed Limit Control (VSLC) and field results show that the application of VSLC can improve the LoS of an urban highway regarding travel time, vehicle emissions and accident rate.

In order to choose the best control law and its configuration parameters, evaluation and verification in various simulations has to be done prior real world implementation. For this purpose, the urban highway segment, where VSLC wants to be applied, has to be modeled and calibrated with real traffic data to ensure accurate simulation results. After that, appropriate control law has to be chosen and adjusted to the

congestion severity and traffic demand change rates. Particular attention has to be given today to ecological aspects, meaning that the effect of the applied speed limit controller on vehicle emissions also has to be evaluated.

Therefore, in this Internship, the whole procedure needed to choose an appropriate controller for VSLC has been done. The procedure will include modeling of an urban highway segment, model calibration using real traffic data, implementation of three different controllers for VSLC, and their evaluation using traffic and ecological parameters including comparison with the case when no VSLC is applied.

## 2. Used software

Since real traffic data need to be simulated for an evaluation of the current traffic situation and, later, for an evaluation after applying some control traffic systems, it is necessary to use appropriate software tools. That means, firstly, it is necessary to simulate the examined traffic data using a microscopic traffic simulator. In this report, the software Verkehr In Städten – SIMulationsmodell (VISSIM) (“Traffic in cities – simulation model” in English). After that, the Matlab platform allows the implementation of a controller for VSLC, its simulation in combination with VISSIM and finally to analyze the data using figures, 2-D and 3-D graphs for seeing where are the problematic points regarding the traffic flow. Finally, using the results from the VISSIM simulation it is important to evaluate the ecological aspects using the software EnViVeR.

### 2.1. VISSIM

VISSIM is a microscopic multi-modal traffic flow simulation software package developed by PTV Planung Transport Verkehr AG in Karlsruhe, Germany. Basically, VISSIM is a microscopic simulation program for modeling multimodal transport operations, which enables the user to test different scenarios before to put a situation into practice. Therefore, this simulator is being used worldwide by the public sector, consulting firms, and universities. Furthermore, it is also possible to perform simulations of pedestrians by using the Wiedemann model. However, this technical report will not deal with this last feature since only a highway section will be modelled and simulated. The VISSIM interface can be seen in Fig. 1.

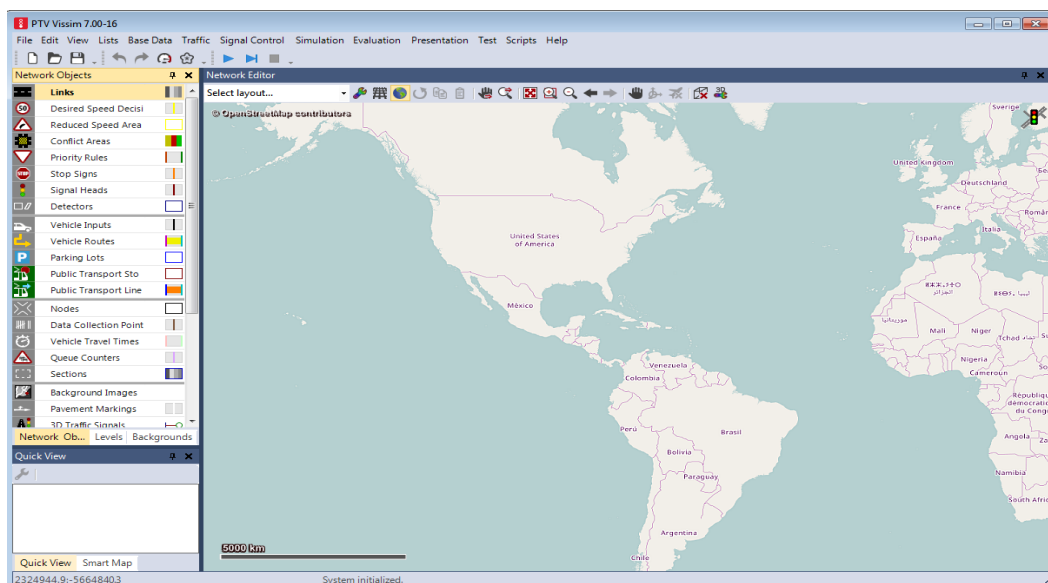


Figure 1 - VISSIM interface.

For this internship, the whole procedure of how to model a road network and how to enter traffic data into this program to simulate a real traffic situation was learned. That means, all of the necessary steps for building a calibrated traffic simulation model, which should represent the real situation into the software were examined and made.

Firstly, all of the needed VISSIM tools were studied in order to obtain the knowledge how to model a road network. After that, some configurations about how to fill the road network with vehicles were learned as, for example, the routing decisions and the vehicle inputs. Finally, for reaching the desired situation, the settings of important traffic model parameters were examined, which enable the calibration of the implemented road network with real traffic data. A simple example of a highway section with two lanes, one on-ramp, and one off-ramp modeled in VISSIM is shown in Fig. 2.

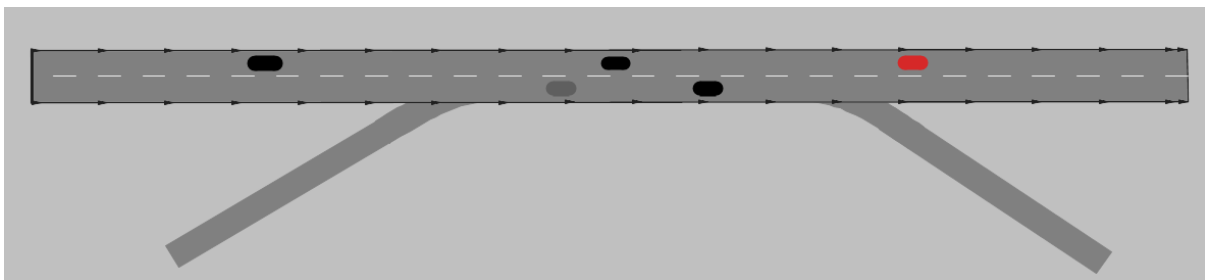
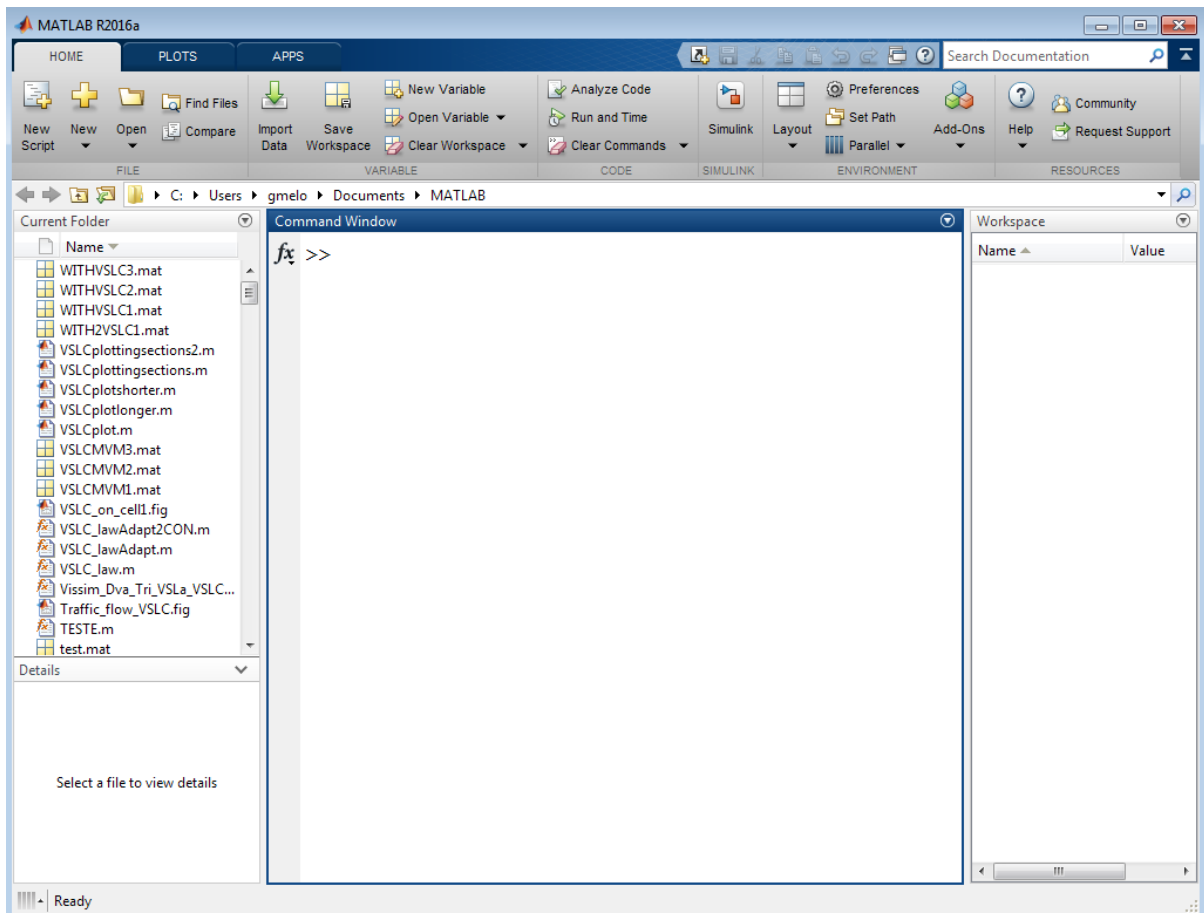


Figure 2 - Simple example of a designed model.

## 2.2. Matlab

The Matlab platform is used to solve engineering and scientific problems. That means, it is used usually, among others, for machine learning, signal processing, image processing, computer vision, communications, computational finance, control design, robotics. It is a good way to express computational mathematics. The initial Matlab interface is shown in Fig. 3.

Furthermore, when creating graphic representations using this platform, it becomes easy to first visualize and then gain insights from various data. That is the main reason to use this tool to help to analyze traffic data. This means that the traffic data can be analyzed easily and, after that, it is possible to link the Matlab platform with the micro-simulator VISSIM. Additionally, various toolboxes in Matlab enable also the implementation of various control laws.



**Figure 3 - Matlab initial interface.**

To learn how to make good figures in Matlab, its main tools were studied. That means, one has to learn how to use this platform from the first steps, as for example how to initiate a code to more complex activities, as for example how to build 3-D graphs. Therefore, for doing that, it was necessary to obtain the knowledge how to access Excel files from a Matlab code, how to configure figures, how to access matrices, how to implement a control law, etc.

In the beginning of this internship, the main usage of Matlab was to analyze the traffic data to obtain the characteristics of the current traffic situation. The 3-D graphs were very useful for that. With using 3-D graphs, it became easy to find where the congestions were happening in the analyzed period. These graphs were composed by three axes, which represented the time, the milepost and the traffic flow. It is possible to see, for example in Fig. 4, that the places which have the red color are congested. The same analysis was done for the occupancy and for the speed. This kind of analysis will be very useful for choosing where the traffic control system should be applied.



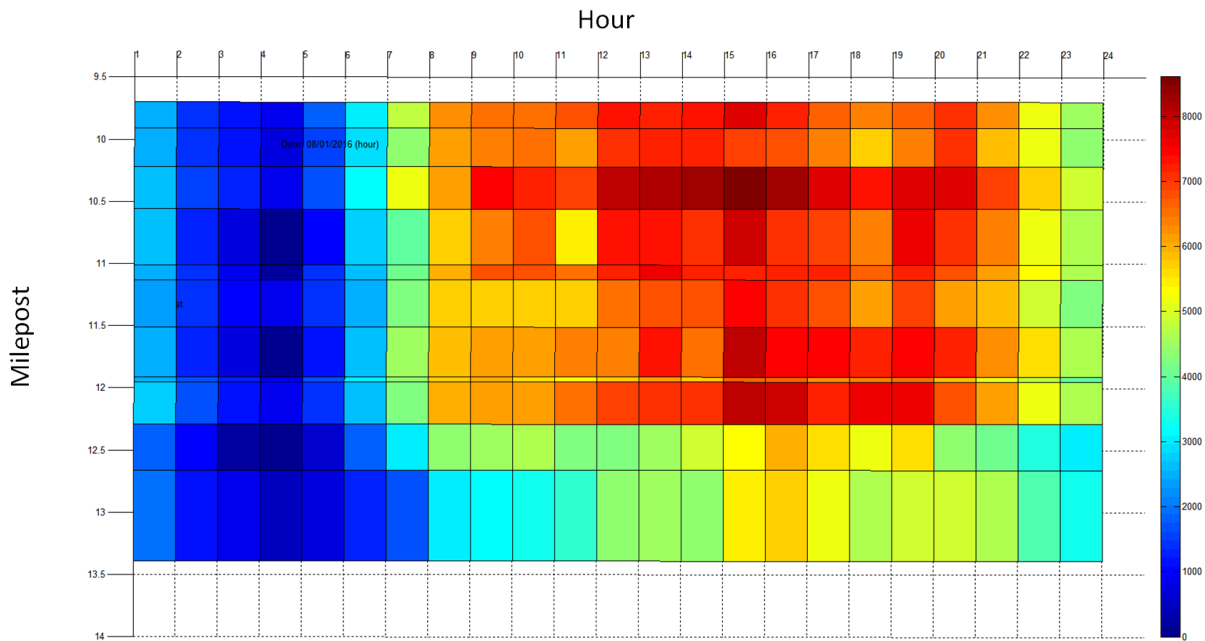


Figure 4 - Example of 3-D graph in Matlab.

After analyzing the traffic data, the Matlab usage got more complicated and its main function for this project has changed, but with this fact will be dealt later in this technical report.

### 2.3. EnViVeR

The EnViVeR program enables to combine results of traffic simulation software (VISSIM, for example) and emission models. It allows the simulation of the environmental traffic impact, meaning emissions of vehicles. That means, it helps to find a good solution for the dilemma traffic flow LoS versus emission values.

It is possible to see the initial interface of EnViVeR in Fig. 5. During the internship, all of the necessary tools for connecting the VISSIM simulation results to the mentioned software were studied, becoming possible to get the emission rates of exhaust gasses during the simulation. This software makes it easier to analyze the implications of a traffic control system when it comes to ecological aspects. That means, it is necessary to solve the traffic problems, but at the same time, the emissions should be acceptable also. The software responsible for showing if it is happening or not is EnViVeR. An example of obtained emission results is shown in Fig. 6.

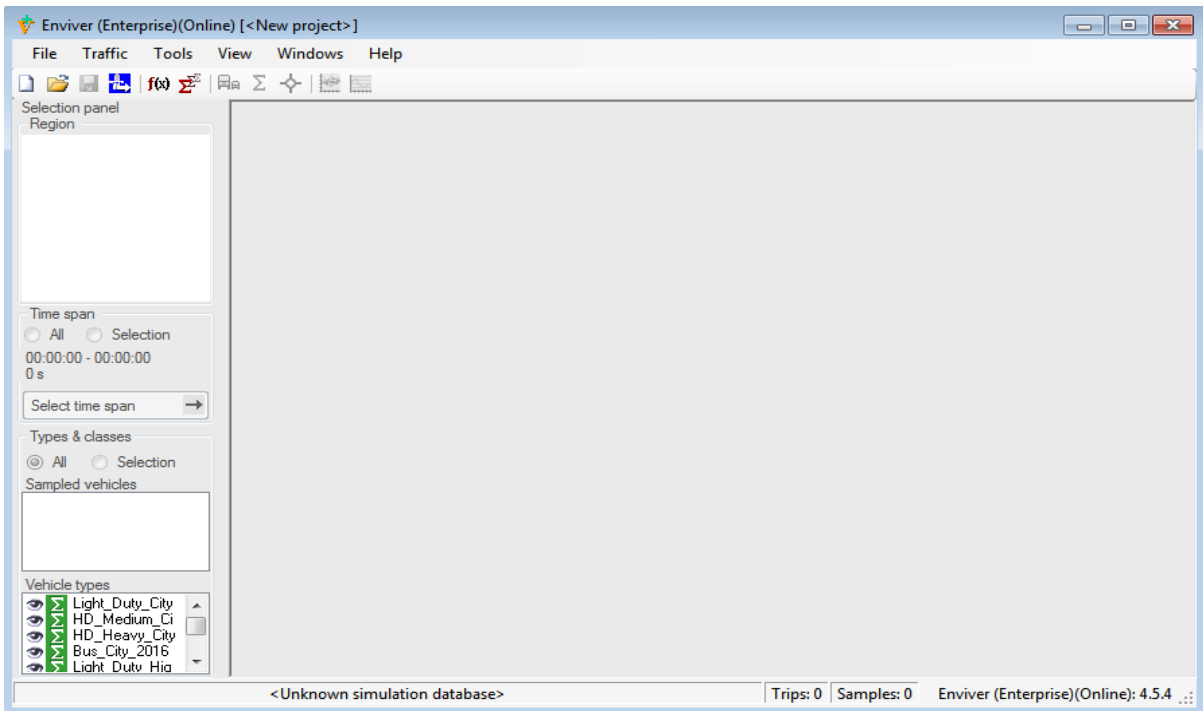


Figure 5 - EnViVeR initial interface.

The screenshot shows the "Results" window with a "Total" tab selected. The table displays the following data:

Total emission:		
CO2	NOx	PM10
1.731e+06 g	4843 g	280 g
7.886e+06 g/h	2.207e+04 g/h	1276 g/h
265 g/km	0.7418 g/km	0.04288 g/km

At the bottom of the window, there are buttons for "Create report", "Export emissions", "Copy data", "Project settings", and "Close".

Figure 6 - Emission results extracted from EnViVeR.

## 2.4. Simulation framework

Three software tools were presented in this chapter and each one has its own function. However, the most useful functions were performed by the connection between them.

The first connection, which has been done involves the software VISSIM and the platform Matlab. This connection was done by using the VISSIM interface called VISSIM-COM. This interface enables that a Matlab code runs the VISSIM simulation and, during this simulation, Matlab gets the useful data, saving it in a matrix result. These saved data are then used for evaluation of the simulated control laws for VSLC. For example, the resulting matrix containing all data extracted from the simulation allows to make a calibrated traffic model because it becomes possible to compare the real data and the simulation data. From this comparison, it is possible to analyze if the model is already calibrated or not. If the model is not calibrated, appropriate parameters, like drive behavior, time step, speed distribution, headway, car-following behavior, among others, need to be changed and this change also can be done by using the VISSIM-Matlab connection. Another procedure possible due to this connection is the implementation of a Variable Speed Limit (VSL) controller when the matrix *result* is accessed during the simulation for checking if the controller for VSLC needs to be activated or not. Basically, if the controller for VSLC is activated, the Matlab code forces a speed limit change during the simulation. The focus of this subchapter is the simulation framework, and the calibration of the simulation model with the implementation of a controller for VSLC will be dealt in more details later.

The mentioned *matrix result* is composed of density data, average speed data, the number of vehicles, traffic flow data, queue lengths on on-ramps, total time spent (TTS) in the network and speed limit changes during the simulation. The density, average speed and the number of vehicles are computed considering cells along the road network. One cell is composed by minimum of two detectors or with a minimum of four detectors if the highway section contains on- and off-ramps. An example of a highway segment with two cells is shown in Fig. 7. After learning what is a cell, it is possible to present the matrix *result* for a general network presented in Fig. 8, where ' $m$ ' is the number of cells, ' $n$ ' is the number of detectors and ' $k$ ' is the number of on-ramps.

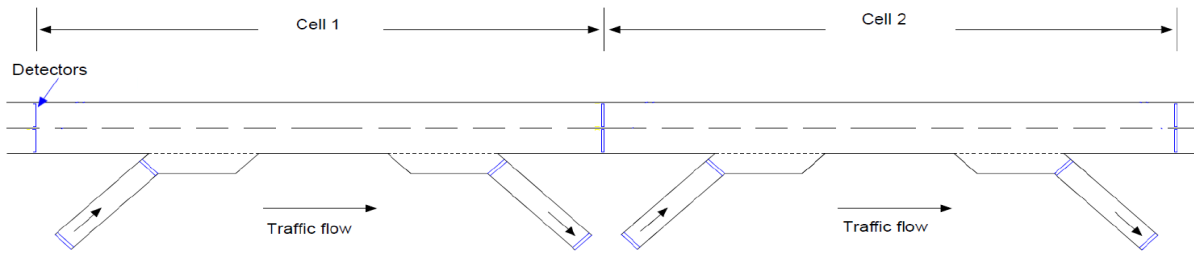


Figure 7 - Example of a segment with two cells.

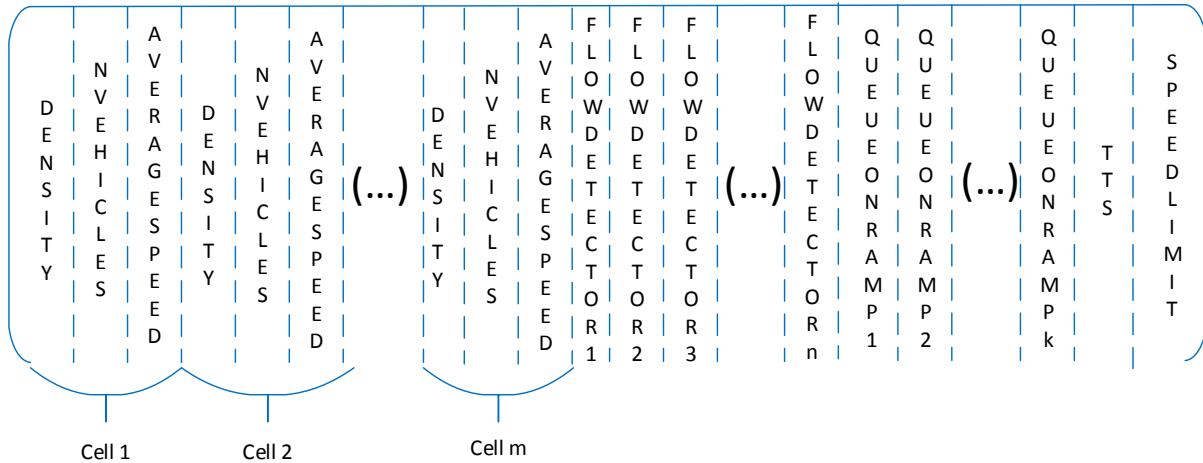


Figure 8 - General configuration of the matrix result.

The next important connection is between the software tools VISSIM and EnViVeR. This connection enables to get the emission results about the whole simulation. That means the software EnViVeR is able to import the VISSIM results and calculate the emission of exhaust gasses that would happen during the whole simulation, which can allow checking the viability of a traffic control system regarding the ecological parameters.

The three mentioned software tools are connected indirectly with the purpose to implement chosen control traffic systems and evaluate the implications of these systems on an examined highway segment. In general, the Matlab code runs the VISSIM simulation, which contains the road network model and the traffic data, to obtain the measurements and deciding if the controller is needed or not. After the whole process between Matlab and VISSIM, the collected traffic parameters are given to EnViVeR, which together with the vehicle characteristics calculates the vehicle emissions. The used simulation framework is given in Fig. 9.

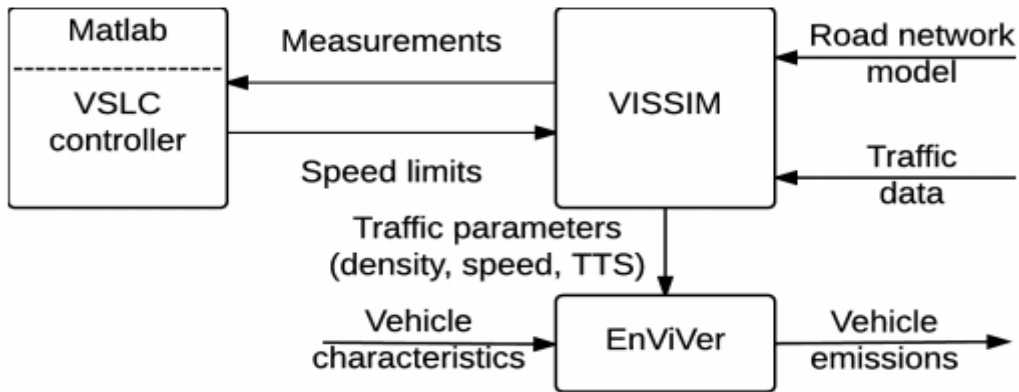


Figure 9 - Simulation framework [1].

### 3. Traffic databases

Since evaluation and verification in simulations have to be done before the real world implementation of a traffic control system, it is necessary to represent a real case of a highway segment in a simulation. For this, all of the traffic data about this segment are needed. Because of this, there are some available databases, where it is possible to obtain the needed traffic data. This chapter will deal with this kind of database to show how the traffic data were extracted, enabling all of the further analysis.

Performance Measurement System (PeMS), Minnesota database (MnDOT) were the databases considered during this internship. Each database was examined from the first steps to choose which one is the best to use for the purpose of this internship.

#### 3.1. PeMS

The PeMS database is a publicly accessible traffic database available on the Internet. It means that, if one has an account (this account is free to obtain), one has access to real-time and historical traffic performance data in many useful formats, like in charts, tables, text, etc. It can provide geometrical data about the spatial configuration of the highway, data about detectors placements, traffic data from detectors, etc. The PeMS initial interface is shown in Fig. 10.

This online traffic database in particular is only about highways of the State of California, USA. To facilitate finding the location of a highway, the State of California has been divided into 12 districts for that database as it is listed below:

- District 1: Northwest;
- District 2: Northeast;
- District 3: North Central;
- District 4: Bay Area;
- District 5: Central cost;
- District 6: South Central;
- District 7: LA/Ventura;
- District 8: San Bernardino/Riverside;
- District 9: Eastern Sierra;
- District 10: Central;
- District 11: San Diego/Imperial;
- District 12: Orange County.

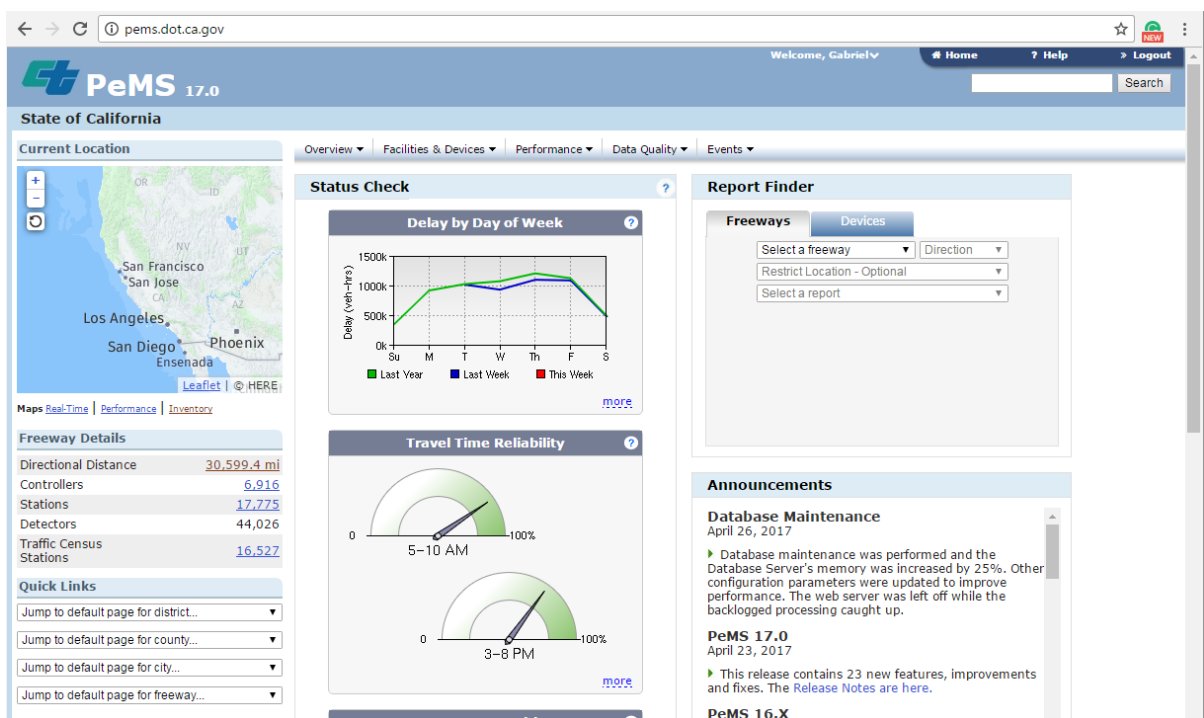


Figure 10 - PeMS initial interface.

As it was mentioned above, this database can provide geometrical data, detector placement data, and traffic data. Regarding geometrical data, it is possible to get details about each segment of a chosen highway, such as the number of lanes of the segment, the segment length, the location of the segment, etc. Besides that, the PeMS database has over 35,000 detectors that report data every 30 seconds. Each detector has an identification (ID) to facilitate its location. Therefore, to get traffic data from a specific detector it is necessary to know the detector ID. However, it is also possible to obtain general data about all detectors as the number of detectors

present in a particular district, for example. The detectors are very important for getting traffic data because the flow data, speed data, density data, among others are extracted from their measurements.

It is good to mention that it is possible to check the quality of the extracted data. That means the PeMS database has a feature, which enables checking how many detectors were working properly when such data were extracted. This is very useful when it comes to the viability of an implementation of a traffic system because it is possible to calculate statistics even if the extracted data do not represent exactly the real situation.

### **3.2. Minnesota database**

The Minnesota database (MnDOT) is also a publicly accessible traffic database available on the Internet. It is about the entire State of Minnesota, USA. That means, it is possible to access historical performance data in many useful formats, like in form of a report, table, graph and a map throughout the area. Since the map format is the easiest and quickest way to analyze the data, just this format was used and an application available in this database, called Traffic Mapping Application (TMA), was used for this purpose. The initial interface of the interactive map can be seen in Fig.11.

As in PeMS, the State of Minnesota is divided into Districts in this database. That means the State of Minnesota has been fragmented in 9 districts to facilitate the location of the highways. The districts were numbered from 01 to 08 and, in addition, there is a district called "Metro". There is a list to know which district contains which city into this web page and it is possible to see a part of this in Fig. 12.

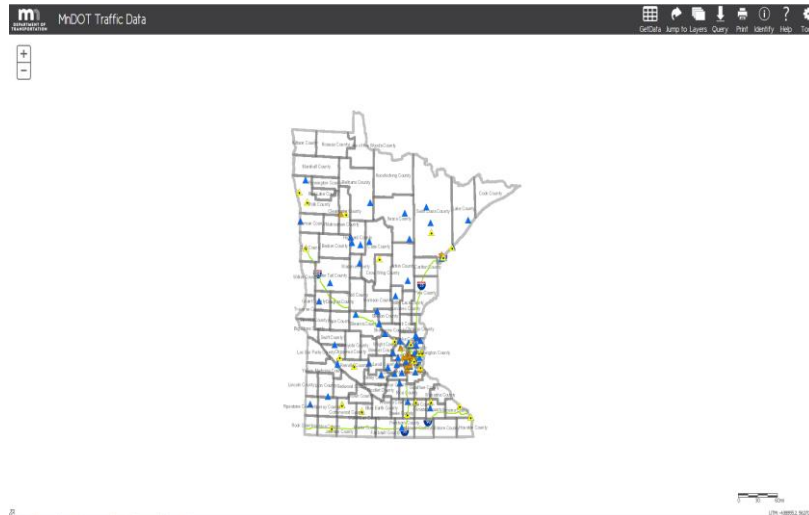


Figure 11 - TMA interface.

## Find your MnDOT district

Find your city in the list below to determine the corresponding MnDOT district.

[A](#) | [B](#) | [C](#) | [D](#) | [E](#) | [F](#) | [G](#) | [H](#) | [I](#) | [J](#) | [K](#) | [L](#) | [M](#) | [N](#) | [O](#) | [P](#) | [Q](#) | [R](#) | [S](#) | [T](#) | [U](#) | [V](#) | [W](#) | [Z](#)

City	MnDOT District
Ada	<a href="#">2</a>
Adams	<a href="#">6</a>
Adrian	<a href="#">7</a>
Afton	<a href="#">M</a>
Aitkin	<a href="#">3</a>
Akeley	<a href="#">2</a>
Albany	<a href="#">3</a>
Albert Lea	<a href="#">6</a>
Alberta	<a href="#">4</a>

Figure 12 - Examples of districts in Minnesota.

Regarding the available data for extracting from this database, it is also possible to collect geometrical data, detector placement data and traffic data.

### 3.3. Slovenian database

The examined Slovenian database is organized in a CD, which is released every year. It contains information collected from counting stations and emergency manual counts in Slovenian highways. The Slovenian database initial interface can be seen in Fig. 13. This example is related to the year 2015.



PROMET 2015		ŠTETJE	AVTOMATSKA ŠTETJA	ROČNA ŠTETJA
<b>Opis metodologij štetij</b> Uvod 1. <a href="#">Ročna štetja</a> 2. <a href="#">Avtomatsko štetje prometa</a> 3. <a href="#">Podatki o prometu na avtocestah in hitrih cestah</a> 4. <a href="#">Končni podatki o prometnih obremenitvah</a>		<h2 style="text-align: center;">UVODNIK</h2> <p>Izšla je zgoščenka ŠTETJE 2015, na kateri so zbrani podatki iz avtomatskih števnih mest v letu 2015.</p> <p>Promet na privzetih števnih mestih še ni bil ocenjen v času izida zgoščenke, zato bo objavljen kasneje v publikaciji Promet 2015 in na naši internetni strani.</p> <p style="text-align: right;">Direkcija RS za infrastrukturo Sektor za evidence o cestah, informatiko in arhiv</p>		
<b>Pregled števnih mest</b> Karta števnih mest Pregled števnih mest Tip števca na števnem mestu Pregled izrednih štetij v križiščih Pregled izrednih štetij na presekih				
<b>Rezultati štetij</b> Štetje 2015 Pregled rasti prometa Pregled rasti tovornega prometa				
<b>Rezultati meritev obremenitev</b> 1. <a href="#">Uvod</a> 2. <a href="#">Mostni WIM sistemi za tehtanje vozil med vožnjo</a> 3. <a href="#">Meritve v letu 2015</a> 4. <a href="#">Točnost rezultatov</a> 5. <a href="#">Normiranje podatkov o prometu</a>				

Figure 13 - Slovenian database initial interface.

As it is possible to see in the Fig. 13, this database has only the Slovenian language. Due to this motive, the examination of the present data was not deeply done and the focus kept on the other two databases.

### **3.4. Comparison of the examined traffic databases**

Since the Slovenian database was not deeply examined because of the used language, the selection of a suitable database for being used during the whole internship considered only the PeMS and Minnesota databases.

Despite both database are able to provide all of the needed data for the research done in this internship, only one of them will be used. Therefore, a comparison between the data collection ways is necessary for seeing which one can be more useful and which one is easier to handle.

Regarding the geometrical data, the PeMS database has more information about a segment, like the number of lanes for example. Furthermore, the PeMS way to expose the data is more organized and accurate than MnDOT.

About detectors placements, MnDOT has not a simple way to get data as in PeMS, because rather than to search for a specific detector, one needs to search a lot of detectors around a point and, then, to find the desired detector. That means the MnDOT does not have an easy way of searching for a specific detector as PeMS.

Furthermore, regarding traffic data, it was possible to notice that the PeMS database has more details about this data type. Besides that, the way to extract the data from PeMS is clearly more organized than from MnDOT.

Finally, in general, the database about the State of California is more organized and the way to collect data is much easier to understand, because the data from different times are arranged individually. That means, in the case of MnDOT, in the same application all data about all measurement times are showed, making it difficult to analyze and extract the needed traffic data.

Therefore, because of the reasons mentioned above, the PeMS database was used for collecting all of the necessary data for the presented analyzes in this internship.

#### 4. Implemented simulation models

It was necessary to select a real highway segment for modeling and applying the controllers for VSLC systems in this internship. Such selection was done considering a few existing articles regarding traffic control system analysis. Of course, since the previously mentioned available database has data only about the state of California, USA, the studied articles also have considered the highways of this state. Therefore, a selection of seven articles about highway controllers was used and it is listed below:

- 1) Benjamin Coifman, Daniel Lyddy, Alex Skabardonis. *Building on the I-880 Field Experiment [2];*
- 2) Jianlong Z., Andrei B. and Petros I. *Design and Evaluation of a Roadway Controller for Freeway Traffic [3];*
- 3) Jianlong Z., Hwan C. and Petros I. *A Simple Roadway Control System for Freeway Traffic [4];*
- 4) Yun W. and Petros I. *Real-time Parallel Parameter Estimators for a Second-order Macroscopic Traffic Flow Model [5];*
- 5) Hui D., Pan L., Zhibin L. and Liteng. *Evaluating the Effects of Different Control Strategies on Traffic Operations at Isolated Merge Bottlenecks [6];*
- 6) Yun Wang. *Dynamic Variable Speed Limit Control: Design, Analysis and Benefits [7];*
- 7) *Local Freeway Ramp Metering using Self-Adjusted Fuzzy Controller [8].*

The relation between each article and its respective analyzed control system can be seen in Tab. 1. This table also presents the periods, in which the observations were done, the highway in question, the location of each analyzed segment regarding the California districts mentioned in the last chapter, the segment length and the direction of each segment. Some boxes were not filled because the used articles do not have such information.

Table 1 - Selection of examined articles.

ARTICLE	HIGHWAY CONTROLLER	HIGHWAY	DISTRICT	TIME (DAYS)	LENGTH (km)	DIRECTION
1	-	Interstate 80	4	-	-	Northbound
2	Variable Speed Limit Control and Ramp Metering	Interstate 80	4	-	3.5	Northbound
3	Variable Speed Limit Control and Ramp Metering	Interstate 80	4	-	7	Northbound
4	-	Interstate 80	4	26 days in August 2003	-	Westbound
5	Variable Speed Limit Control and Ramp Metering	Interstate 5	11	16:00 to 19:00 on July 22, 2009	2.4	-
6	Variable Speed Limit Control	Interstate 93	-	-	-	Southbound
7	Ramp Metering	-	7	7:00 to 9:00 am on November, 2014	3.91	-

After reading all of these articles, the segment of the article “ A Simple Roadway Control System for Freeway Traffic” was chosen for being examined in this study. This choice was done because it is the most embracing among the presented segments. Therefore, a more embracing analysis becomes possible. Furthermore, it is necessary to model at least 1 km of a highway before the speed limit change location to apply VSLC. That means, the driver should be warned 1 km before needing to change the speed. Therefore, it is necessary to select a long segment.

The chosen segment was divided in two cases: the shorter and the longer segment. This division was done for making it easier to understand the procedures in question needed in this internship in a simple case before to implement them into a more complex case. That means all of the procedures during the report will be presented, firstly, for the shorter segment and, then, for the longer segment. The two highway parts will be presented in continuation.

#### 4.1. Shorter segment

The shorter segment is a stretch of the highway “Interstate 80” located in the State of California, which is part of the District 4 (Bay Area) according to the PeMS database. This segment has 5 lanes, 3.5 km, 7 vehicles detectors, 1 VSLC message sign and 2 on-ramps equipped with ramp-metering (RM). The stretch is shown in Fig 14.

Each detector is located in a certain milepost according to the PeMS database. Therefore, it is possible to make a table showing where all detectors are located, and to show the respective identification (ID) of the detectors (see Tab. 2).

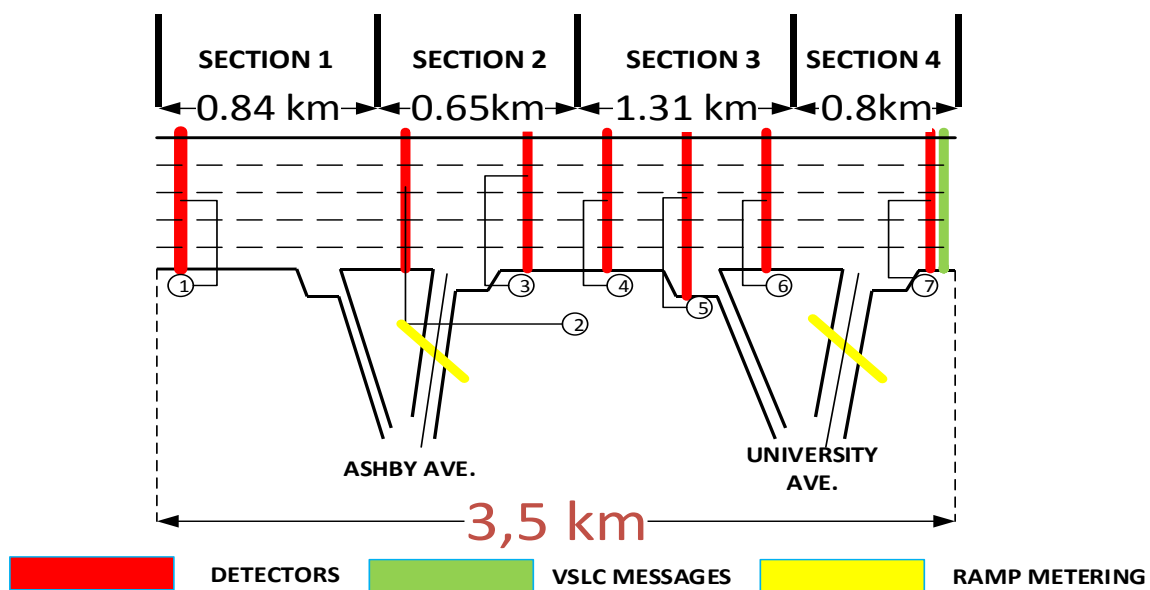


Figure 14 - Shorter segment.

Table 2 - Detectors placements regarding the shorter segment.

Detector number	Mileage (miles)	Mileage (km)	Vehicle detector station (ID)
1	9.7	15.52	403998
2	9.91	15.856	405589
3	10.22	16.352	400679
4	10.56	16.896	401198
5	11.01	17.616	400432
6	11.13	17.808	400728
7	11.51	18.416	400612

## 4.2. Longer segment

The longer segment is the entire segment chosen and mentioned in the beginning of this chapter. That means it is a continuation of the shorter segment. Now, it is made of 5 lanes, 7 km, 12 vehicles detectors, 2 VSLC message signs and 4 on-ramps, but only 3 equipped with RM. The stretch is shown in Fig. 15 and a table showing where is located each detector with its identification can be seen in Tab. 3.

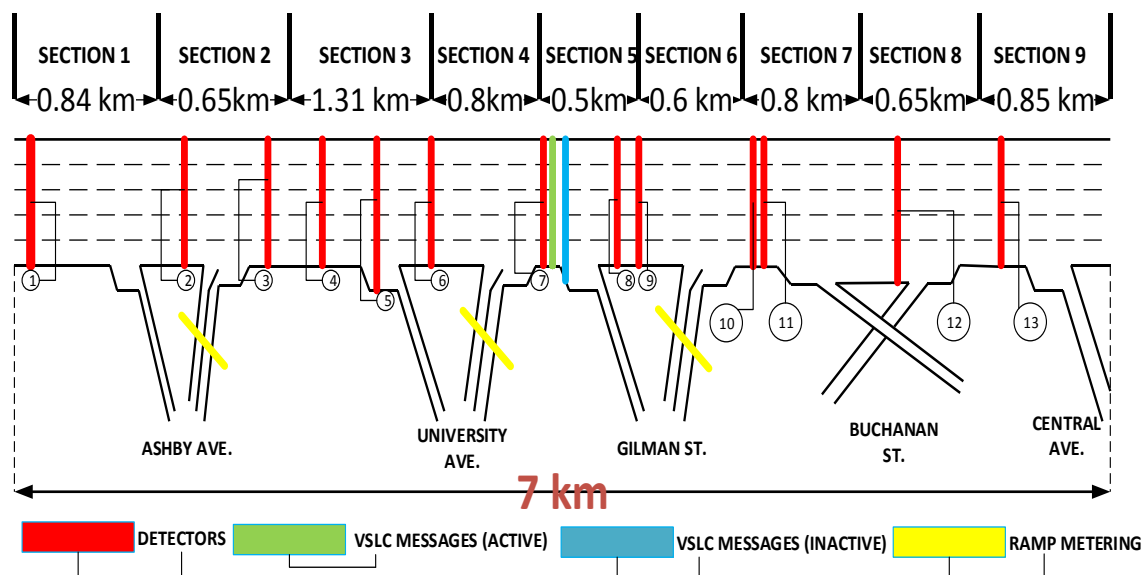


Figure 15 - Longer segment.

Table 3 - Detectors placements regarding the longer segment.

Detector number	Mileage (miles)	Mileage (km)	Vehicle detector station (ID)
1	9.7	15.52	403998
2	9.91	15.856	405589
3	10.22	16.352	400679
4	10.56	16.896	401198
5	11.01	17.616	400432
6	11.13	17.808	400728
7	11.51	18.416	400612
8	11.91	19.056	408632
9	11.95	19.12	401079
10	12.29	19.664	401901
11	12.66	20.256	401239
12	13.39	21.424	402062

### 4.3. Traffic data

The both presented segments were modeled in VISSIM for running a simulation of it. For this, it was necessary to select a period of analysis. That means it was necessary to define a time period, which would be simulated. Therefore, firstly, just in order to start getting the basic usage of VISSIM, a one-day simulation was done. The first considered period was from 00 h to 23:59 h of the day 01/08/2016. All of the needed data for a VISSIM simulation, as for example flow data, occupancy data and speed data were extracted from PeMS and the simulation was completed. It is possible to see these data for all detectors in Figs. 16-18.

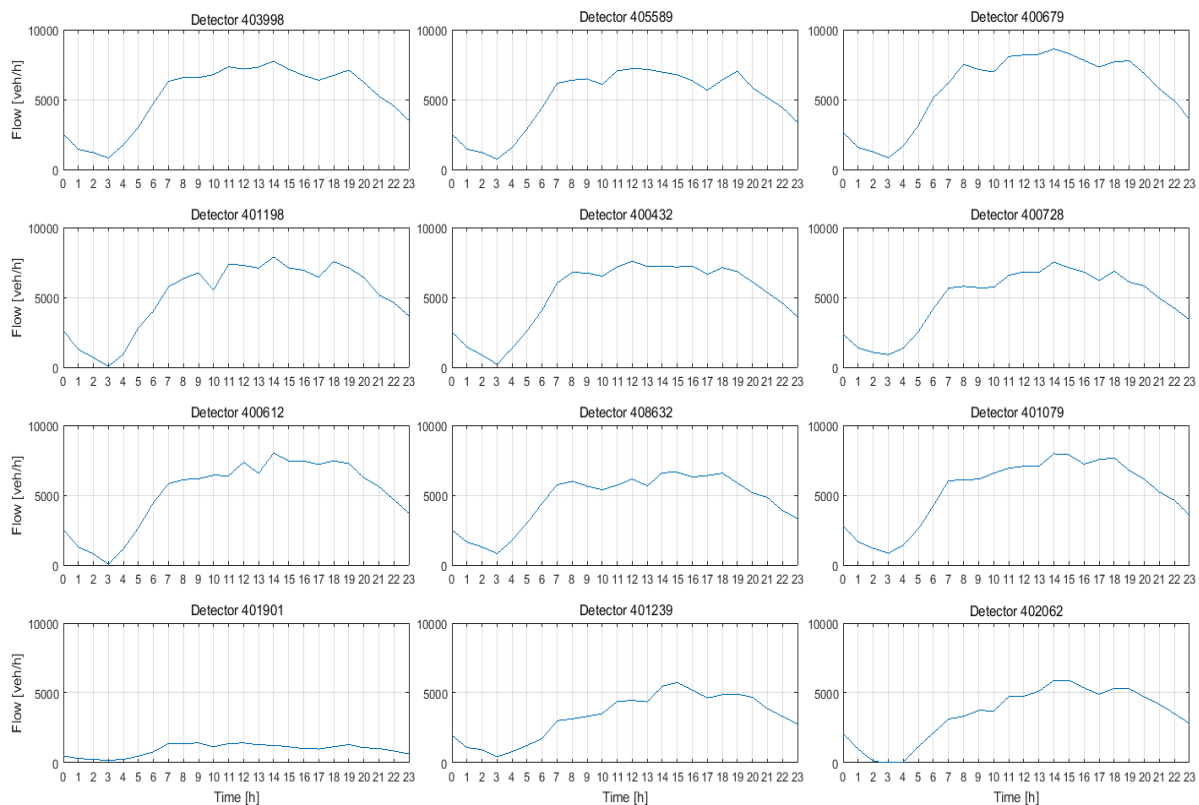
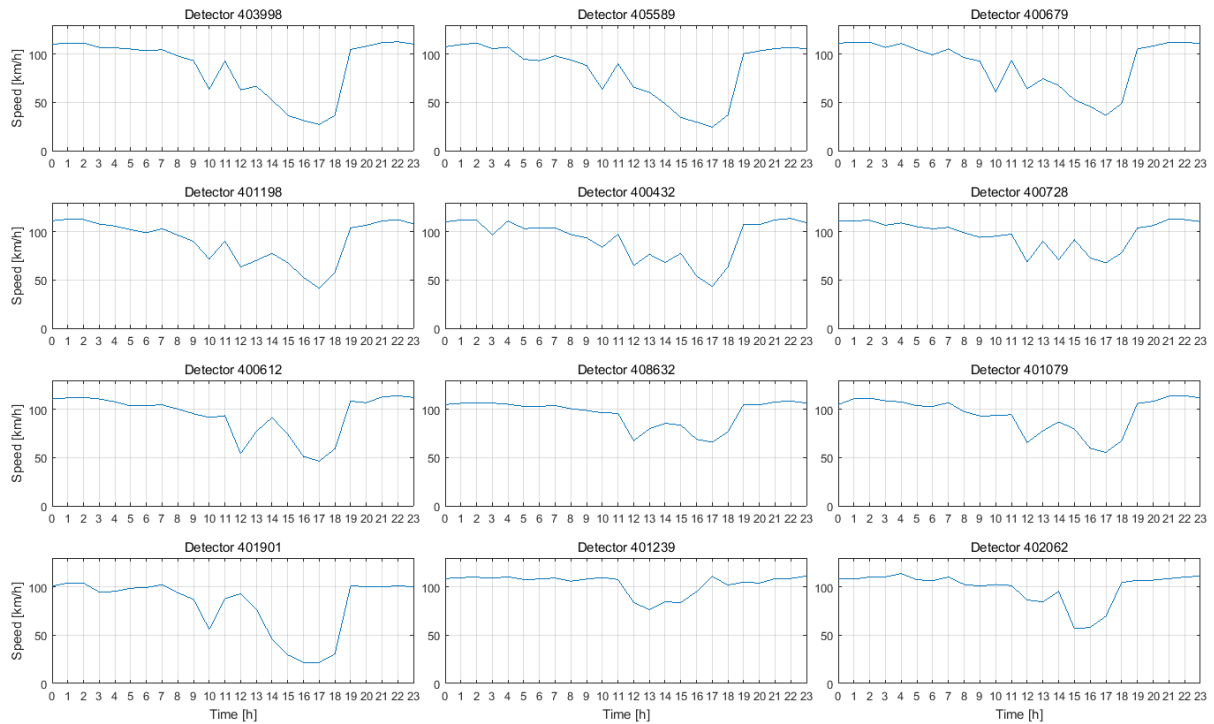
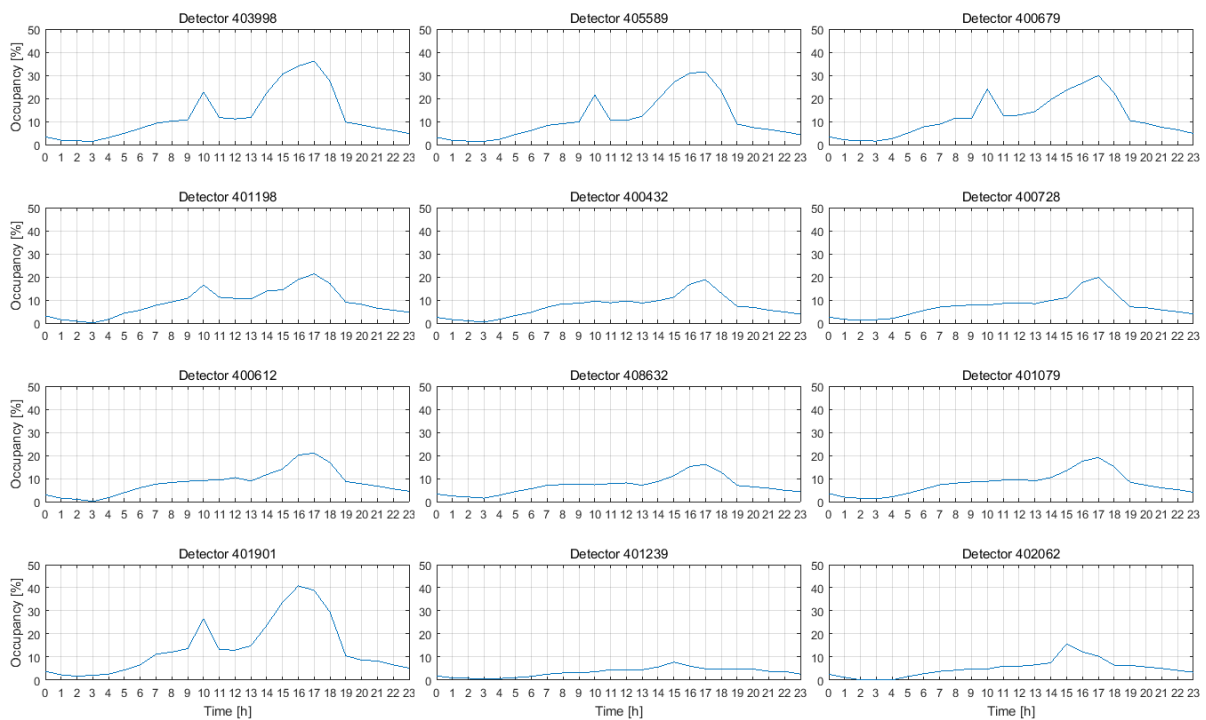


Figure 16 - Flow data about the whole day of 01/08/2016 for each detector.



**Figure 17 - Speed data about the whole day of 01/08/2016 for each detector.**



**Figure 18 - Occupancy data about the whole day of 01/08/2016 for each detector.**

After the mentioned test simulation, two smaller periods were selected for being implemented during the whole research. The both periods are from the same day previously simulated. The first one regards two peak hours in the middle of this day and the second one regards a period in the morning of this day. These periods will be presented in continuation.



### 4.3.1. Noon period

The noon period is composed of two hours, which includes from 12 h to 14 h of the first day of August in 2016. This period is characterized by constant congestions, what makes it harder for the traffic control system to make an appropriate reaction. That means, since the period has congestions at the most part of the time, the controller for VSLC is not able to make significant improvements. Therefore, the idea, in this case, is to see how the traffic control system for VSLC reacts when traffic critical situations are imposed.

All of the traffic data regarding this period can be seen in Figs. 19-21.

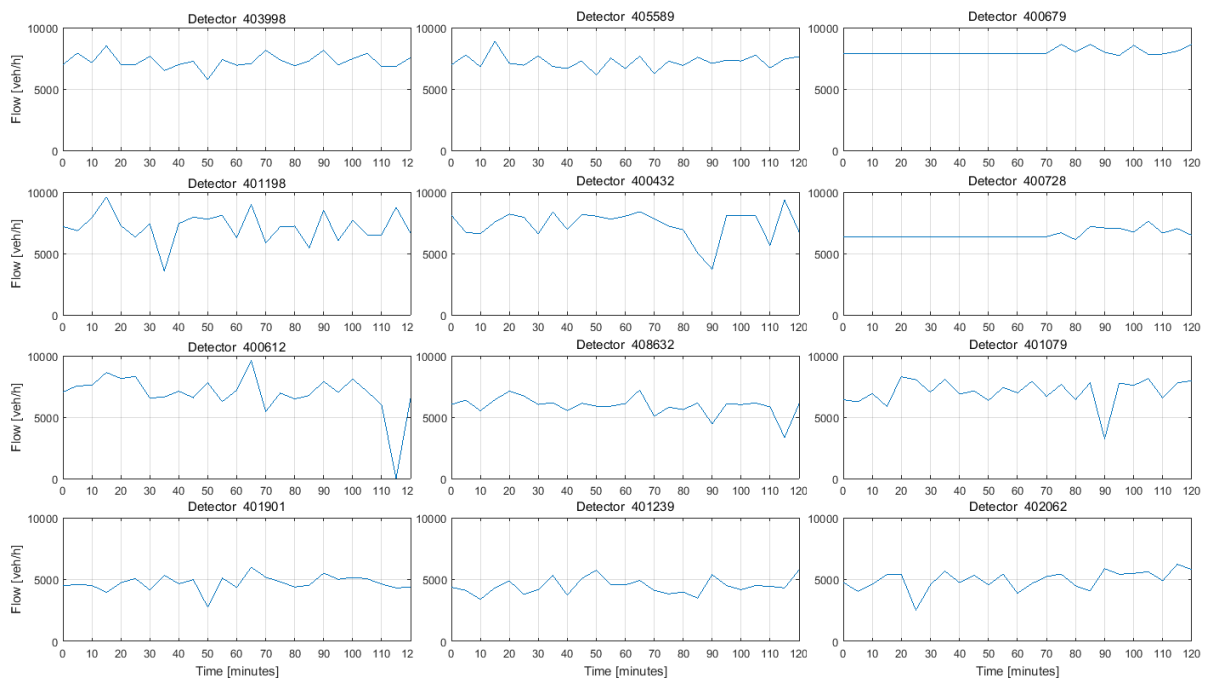
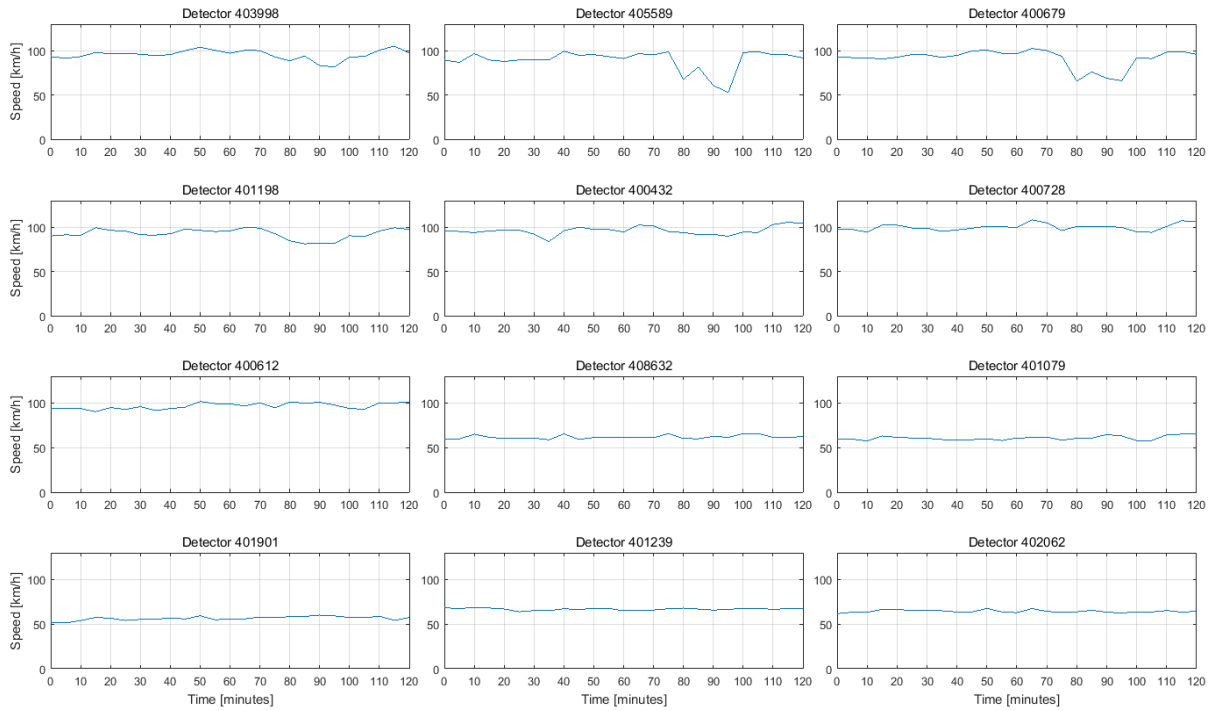
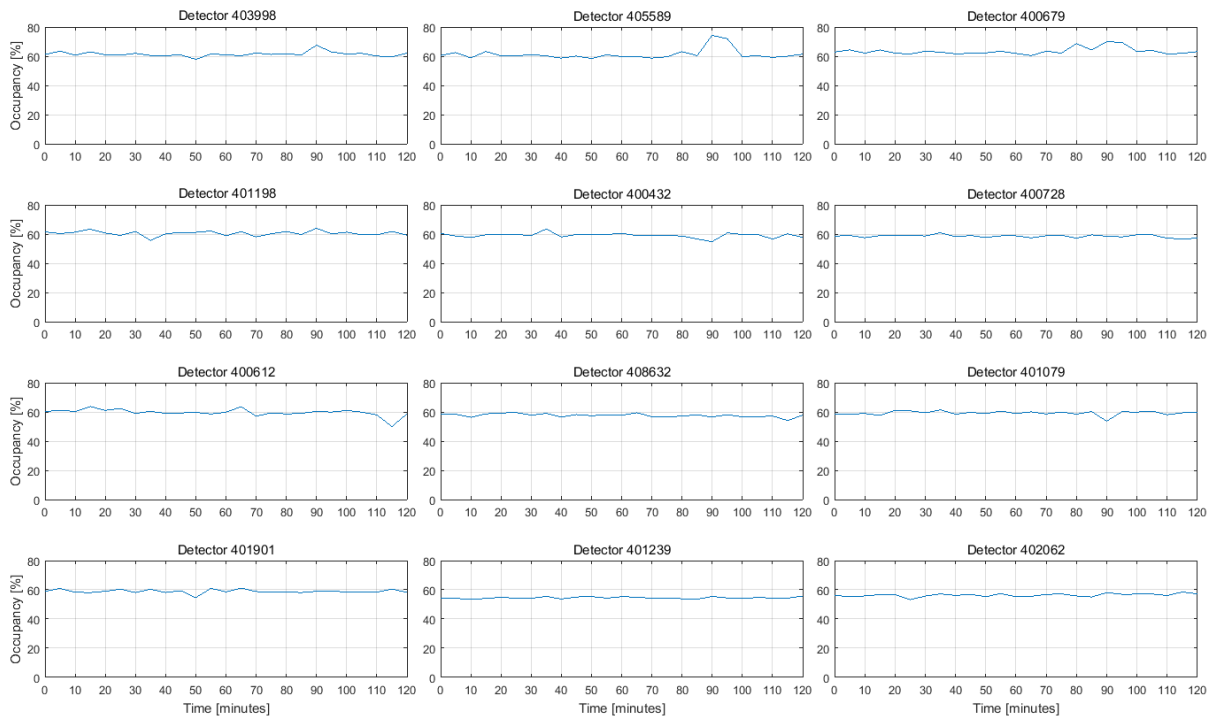


Figure 19 - Flow data regarding the noon period.



**Figure 20 - Speed data regarding the noon period.**



**Figure 21 - Occupancy data regarding the noon period.**

### 4.3.2. Morning period

The morning period is composed of three hours, which embrace the time from 08 h to 11 h of the first day of August in 2016. This period was also analyzed because it is not totally saturated as in the noon period, what enables that a traffic control system can react more appropriately, resulting in significant changes in the current situation. That means it is good to see if the controller can act differently if the traffic situation is not above the critical traffic situations.

All of the traffic data regarding this period can be seen in Figs. 22-24.

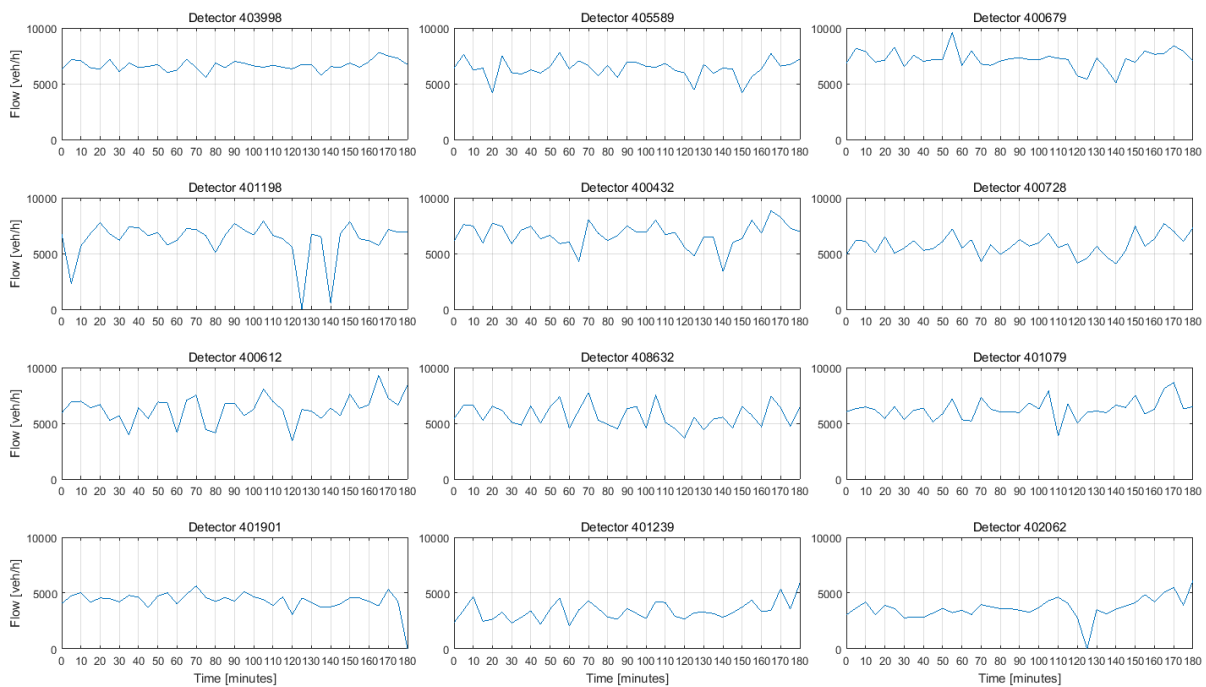


Figure 22 - Traffic flow regarding the morning period.

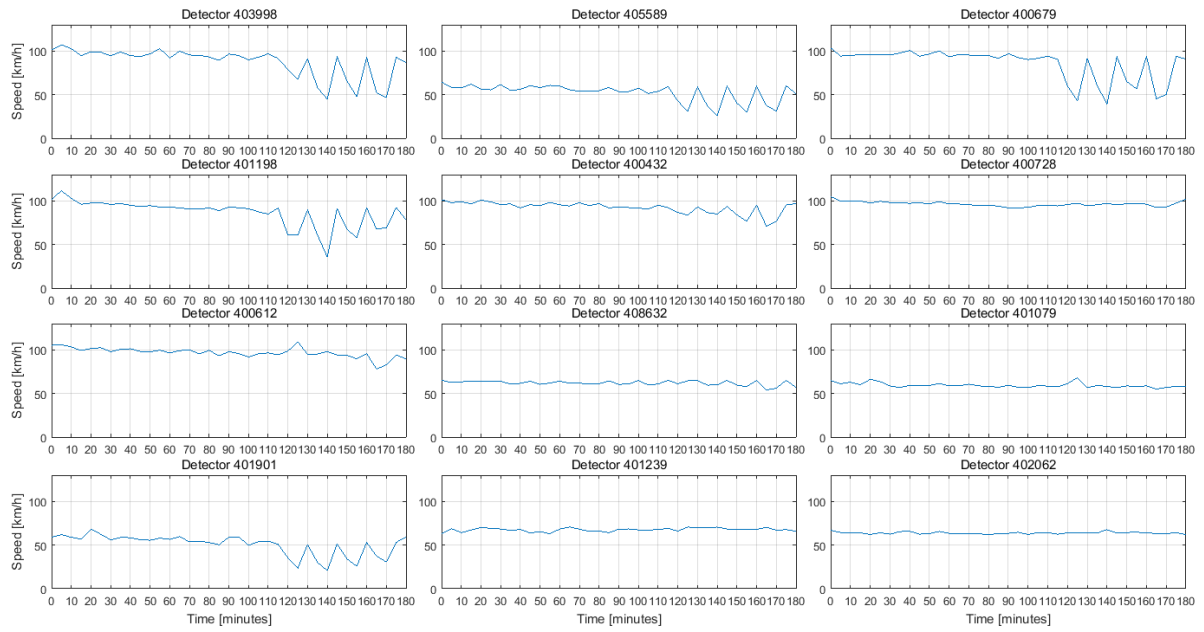


Figure 23 - Speed data regarding the morning period.

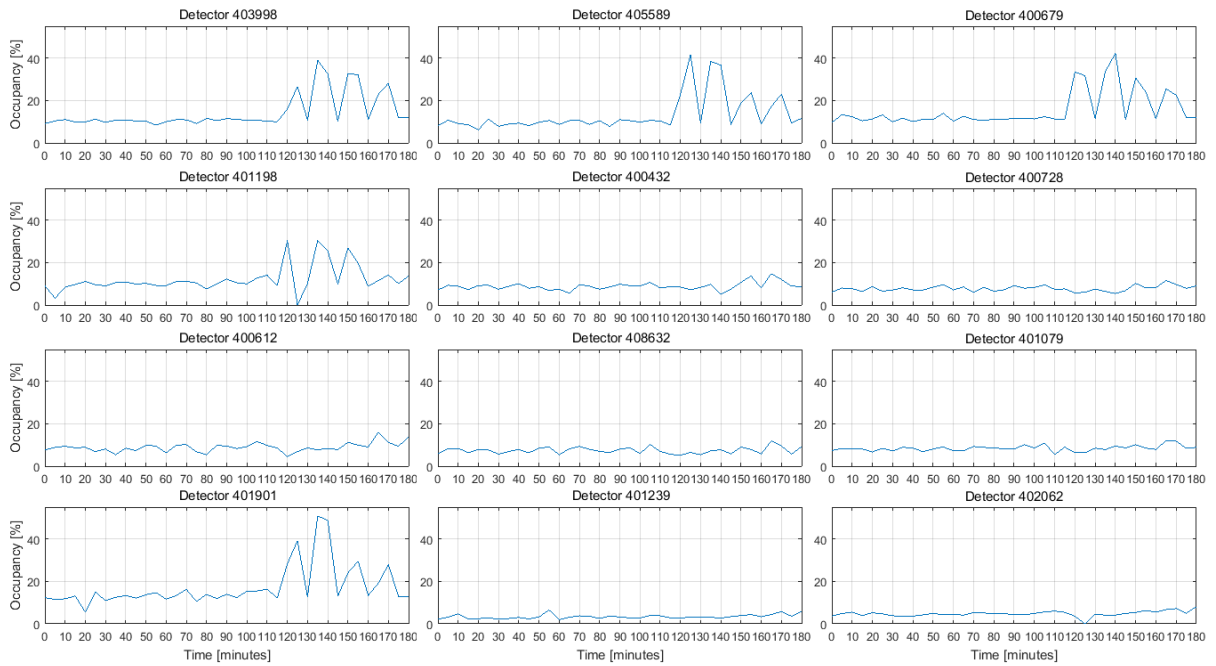


Figure 24 - Occupancy data regarding the morning period.

#### 4.4. Calibration

A spatial modeling of the chosen urban highway section was made and the traffic data extracted from the PeMS database mentioned in the previous chapter were simulated into VISSIM for the both presented periods. It is good to mention that the simulations were executed with a warm-up period for filling the network before the important period (30 minutes for the shorter segment and 70 minutes for the longer segment). After that, a comparison between the data collected from the simulation and the real data from PeMS was done to check if the simulation model can represent accurately the real traffic situation. This comparison was done by using the GEH statistic.

The GEH statistic is a measure used to compare two sets of traffic volumes. Besides that, this formula is used to represent the goodness-of-fit of a traffic model. Therefore, it will be used in this work to check the compatibility between the simulated data and the data from the PeMS database for helping to calibrate the simulation model. The formula in question is shown as follow:

$$GEH = \sqrt{2 * \frac{(M - C)^2}{M + C}}, \quad (1)$$

where M regards hourly traffic volume from the traffic model and C regards real-world hourly traffic count (from PeMS).

It is good to mention that the GEH is not unitless, but has the following unity:

$$\sqrt{\frac{vehicle}{hour}}.$$

Furthermore, to get a good calibration, the GEH statistic for traffic modeling should be less than 5 for more than 85% of the individual links and less than 4 for the sum of all link counts. For individual traffic flows, the rules given in Tab. 4 can be applied.

Table 4 - Rules for applying the GEH statistic formula [9].

GEH less than 5	Acceptable fit, probably OK.
GEH between 5 and 10	Caution: possible model error or bad data.
GEH greater than 10	Warning: high probability of modeling error or bad data.

To facilitate the calculation of GEH statistic, an appropriate code in Matlab was written. That code accesses the matrix *result* mentioned in section 2.4, which contains all collected data during a simulation and accesses the files containing flow data extracted from PeMS at the same time. Finally, the GEH statistic is computed applying the both flow data into the formula.

#### 4.4.1. Shorter segment

The calibration regarding the shorter segment was done comparing the simulated data and the real data for each examined hour by using the GEH statistic. In the first simulations, the results were not satisfactory because the default VISSIM parameters were used. That means, as the parameters combination was being changed, the GEH results were getting better.

For reaching good results faster, appropriate articles about this subject were consulted as, for example, the paper called “*Calibrating VISSIM for the German highway capacity manual*” [10]. From this paper, it was possible to extract a reliable VISSIM parameters combination for a basic highway, which was used for the calibration of the highway stretch used during this internship (see Tab. 5).

Table 5 - VISSIM parameters combination for a basic highway [14].

Basic freeway segments	Passenger cars	Heavy vehicles
<b>Following</b>		
car following model	Wiedemann 99	Wiedemann 99
CC1 (headway time) [s]	1.05	1.05
CC4 (negative ,following‘ threshold) [-]	-0.30	-0.30
CC8 (standstill acceleration) [m/s <sup>2</sup> ]	3.50	2.50
CC9 (acceleration at 80 km/h) [m/s <sup>2</sup> ]	1.50	1.00
<b>Lane Change</b>		
general behavior	right-side rule	right-side rule
cooperative lane change	yes	no
within: maximum speed difference [km/h]	10.8	-
within: maximum collision time [s]	10.0	-
-1 m/s <sup>2</sup> per distance, own [m]	300.00	200.00
accepted deceleration of trailing vehicle [m/s <sup>2</sup> ]	-0.75	-0.50
to slower lane if collision time above [s]	15.00	1.00
advanced merging	yes	no

However, only the mentioned parameters combination was not enough for a really good calibration result. Therefore, besides the parameters changes, it was necessary to do alterations, like adding reduced speed areas before and on on-ramps, setting the speed distribution and creating an extra lane before the off-ramps into the VISSIM simulation. And, after all of the needed alterations, the calibrated model was reached for the both periods, which are presented below.

***-Noon period***

The GEH statistic results were computed for each hour of the examined period as it was mentioned and it is possible to see the results in Tab. 6.

**Table 6 - Final calibration results for the shorter segment regarding the noon period.**

	Final Result		
	GEH (12h)	GEH (13h)	GEH(14h)
Detector 403998	5.2	1.1	3.2
Detector 405589	3.8	5.3	8.2
Detector 400679	5.8	2.9	6.5
Detector 401198	0.9	16.2	2.2
Detector 400432	4.1	0.3	5.2
Detector 400728	3.0	2.5	4.3
Detector 400612	2.7	4.4	7.3
GEH Average	4.5		
Percentage (< 5)	61.90%		
Percentage (< 10)	95.23%		
GEH>10			
5<GEH<10			
GEH<5			

***-Morning period***

The same mentioned procedure was done for the morning period and the results are shown in Tab. 7.

**Table 7 - Final calibration results for the shorter segment regarding the morning period.**

	Final result			
	GEH (08h)	GEH (09h)	GEH(10h)	GEH(11h)
Detector 403998	2.43	6.09	1.85	6.5
Detector 405589	3.49	2.08	8.84	6.3
Detector 400679	4.01	5.17	6.49	2.7
Detector 401198	0.22	5.71	0.45	4.5
Detector 400432	9.62	8.21	5.65	3.2
Detector 400728	0.62	6.84	2.92	2.2
Detector 400612	6.05	10.95	0.28	6.9
GEH Average	4.65			
Percentage (< 5)	50%			
Percentage (< 10)	96.42%			

GEH>10	
5<GEH<10	
GEH<5	



#### 4.4.2. Longer segment




The whole described procedure done for the shorter segment was applied for the longer segment. At this time, the parameter changes were not necessary, because the same settings used before were used in this case. That means, it is not necessary to check again which combination of parameters is good for this model. Therefore, the calibration was done for the both periods as it can be seen in continuation.

#### *-Noon period*

After computing all of the GEH statistic results for each detector and for each hour, it is possible to see in Tab. 8 the calibration results for the noon period.

Table 8 - Final calibration for the longer segment regarding the noon period.

	Final Result		
	GEH (12h)	GEH (13h)	GEH(14h)
Detector 403998	7.2	5.1	0.9
Detector 405589	6.3	4.4	6.1
Detector 400679	0.2	6.8	8.2
Detector 401198	3.3	12.6	7.1
Detector 400432	4.1	3.9	2.5
Detector 400728	3.7	5.2	4.8
Detector 400612	0.6	0.8	6.9
Detector 408632	1.3	0.7	1.2
Detector 401079	0	3.6	4.2
Detector 401901	3.1	2.2	0.9
Detector 401239	0.8	13.4	6.6
Detector 402062	4.8	5.1	6.9
GEH Average	4.3		
Percentage (< 5)	61.11%		
Percentage (< 10)	94.40%		




GEH>10	
5<GEH<10	
GEH<5	

### ***-Morning period***

Following the same procedure, it is possible to analyze the GEH results in Tab. 9 for the morning period.

**Table 9 - Final calibration for the longer segment regarding the morning period.**

	Final Result			
	GEH (08h)	GEH (09h)	GEH(10h)	GEH(11h)
Detector 403998	3.2	3.9	5.1	1.9
Detector 405589	4.6	4.2	9.6	9.5
Detector 400679	10.0	9.6	8.3	10.7
Detector 401198	9.1	0.7	7.1	0.9
Detector 400432	4.8	3.8	9.9	3.3
Detector 400728	7.9	5.8	5.1	4.4
Detector 400612	3.8	18.2	2.8	4.1
Detector 408632	2.8	8.8	2.6	1.7
Detector 401079	1.3	9.8	4.9	1.9
Detector 401901	1.1	6.0	4.5	2.4
Detector 401239	4.7	4.4	8.2	7.3
Detector 402062	2.0	0.2	9.5	10.8
GEH Average	5.6			
Percentage (< 5)	56.25%			
Percentage (< 10)	93.75%			

GEH>10	
5<GEH<10	
GEH<5	

### **4.4.3. Discussion**

As it was possible to see, all of the presented calibration results have some problematic points, where the obtained GEH statistic is greater than 10. Many tries for solving these problems were executed, but the bad results in this points have remained. Therefore, seeking to figure out what was happening in these places, the data of such detectors were analyzed. For that, appropriate graphs comparing the PeMS data and the simulation data were done. For example, there is a problematic point in the shorter segment regarding the noon period located on the Detector 401198. Analyzing the flow graph about this Detector (see Fig. 25), it is possible to see a considerable oscillation occurring on the PeMS data line around 13 h (60 minutes after the warm-up period). That means that the calibration problem can happen due to a problem with the measurement or it can occur because there is an RM control system in this location, which it is not

being taken into account. Showing others examples, the same conclusion can be done for the Detectors 401198 and 401239 regarding the longer segment in the noon period. It is clear in Figs. 26-27 that the reason of these problematic points is the big oscillation present around 13 h.

Therefore, after analyzing, the current results were taken as acceptable because such problematic points can not be solved since it is impossible to represent such big oscillations in a short time in a simulation without considering the detail influence of all present traffic control systems.

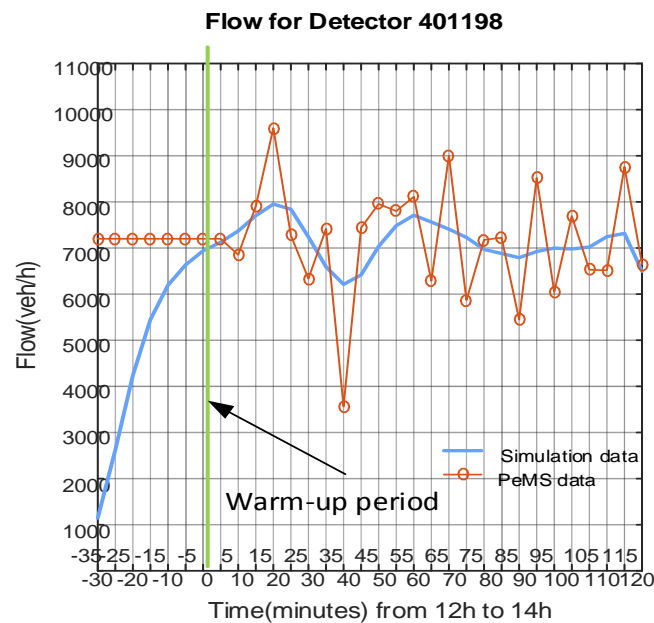


Figure 25 - Comparison between the simulation data and the real data for the Detector 401198 (shorter segment).

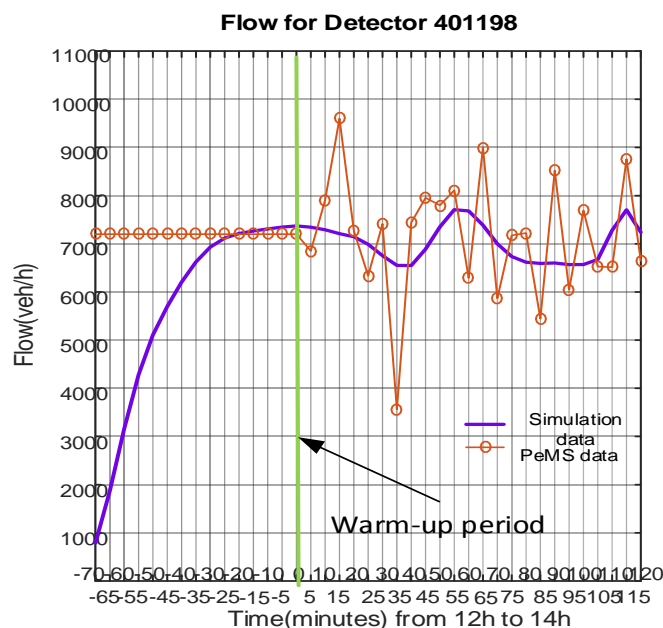
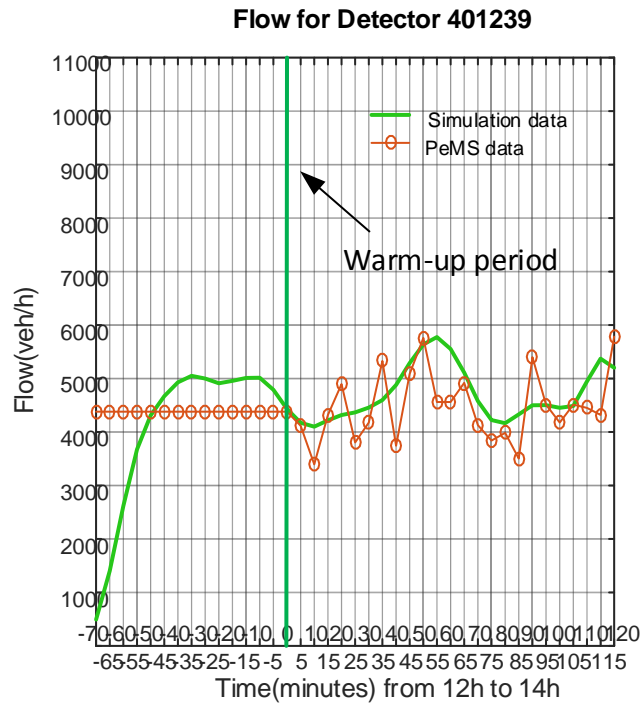


Figure 26 - Comparison between the simulation data and the real data for the Detector 401198 (longer segment).



**Figure 27 - Comparison between the simulation data and the real data for the Detector 401239 (longer segment).**

## **5. Implemented controllers for Variable Speed Limit Control**

On urban highways often VSLC is applied. The goal of VSLC is to change the current speed limit according to the current traffic or weather situation by using variable message signs (VMS) to inform the drivers. Therefore, the speed limit value can be set appropriately to the current traffic conditions increasing traffic throughput and safety, and reducing travel time (T-T) and vehicle emissions. To implement such a VSLC system one has to create a closed control loop i.e. to measure current traffic parameters, apply a controller and present the new speed limit to the drivers. The controller is the central part and it contains a control law with appropriate settings on which the resulting LoS of the controlled urban motorway section depends.

The simulation framework presented in Section 2.4 is used to implement a traffic control system into the simulation in order to make a comparison between several chosen control systems and to see which control law is the most suitable. Additionally, it enables the inclusion of environmental parameters into the evaluation procedure. With this last feature, a better evaluation can be done in comparison when only traffic parameters are used for evaluation because traffic control systems have to improve not only traffic parameters but traffic safety and environmental parameters also. Seeking this analysis, three controllers were implemented, Simple Proportional Speed Controller (SPSC), Mainline Virtual Metering (MVM) and VSLC based on fuzzy logic.

The procedure to apply a controller like that includes a dynamic control of highway. That means the highway current conditions need to be sent to a traffic control center, which needs to verify if it is necessary to apply a traffic controller. For this case, the control center receives the current traffic data containing all features of the traffic conditions and, after analyzing these data, calculates a new speed limit value according to the situation (traffic or weather situation).

Since this is a dynamic system, it becomes necessary to use an application to warn the drivers what is the new speed limit value. This warning application is the mentioned VMS. Of course, the current conditions may not require a speed limit change and the system just maintains the current default speed limit.

Therefore, the whole system can be represented by the diagram presented in Fig. 28. It is good to mention that the current weather

situation also can be considered for applying VSLC, but for the present case only the traffic conditions were considered.

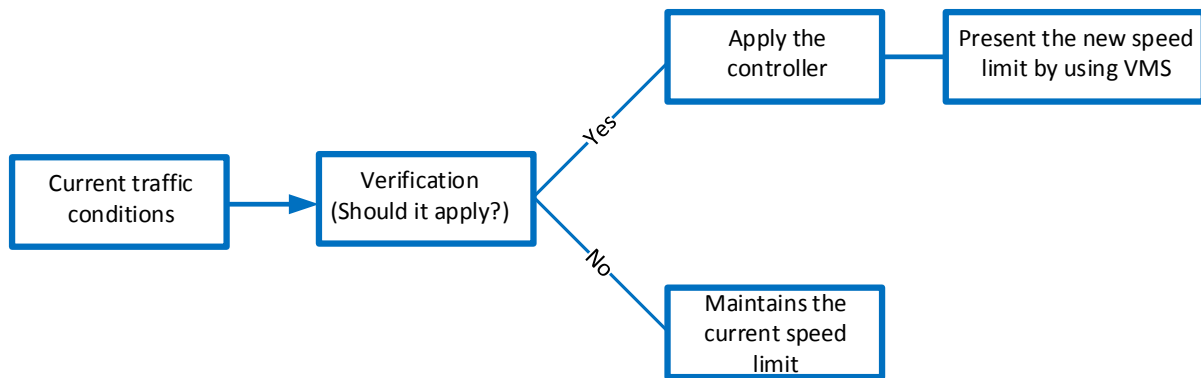


Figure 28 - VSLC system diagram.

Besides knowing how the system works, it is necessary to decide where is the best place to apply it. Some countries decide to apply this controller in places, where accidents are most common because the VSLC raises the safety on urban highways. Furthermore, congestions are most common on highways containing many access ramps, mainly, that ones which connect the highway to an urban area. Therefore, the VSLC needs to be applied to highway segments with a high accident index and, in the same time, highway segments containing many access ramps.

Finally, it is necessary to understand how the system causes these results. The main strategy for almost all results is reducing the speed difference between the vehicles. The greater the homogenization, the greater the safety, the lower the emissions, the better the throughput and the lower the traffic density. For example, the safety increases because the vehicles do not need to make a quick break if the speeds are close to each other. Furthermore, the emissions are reduced because the vehicles do not need to be accelerated all the time for keeping a continuous speed.

### 5.1. Simple Proportional Speed Controller

The SPSC responds to changes in downstream density instead of to try to get a fixed desired density. That means it is also a dynamic system, which needs to compute the density values in a downstream section for analyzing and calculating what is necessary to do in the previous section regarding speed limit changes to ensure the reduction of density and, consequently, the dissolution of congestion.

To apply this controller into a VISSIM simulation, it becomes necessary to learn how its mechanism works. Firstly, the SPSC generates command signals after equally spaced time intervals. After that, the density in the following section is measured ( $\rho_{i+1}$ ) to check if the controller needs to be activated or not.  $C_i$  is the variable responsible for activating or not the controller. If  $C_i = 1$ , the controller is active and if  $C_i = 0$ , the controller is not active. Then, if the controller is activated, it generates the desired speed limit for the current section ( $V_1$ ). In general lines, the system needs to do the following verification ( $k$  is responsible for spacing the subsequent time intervals and  $T_1$  represents the time step):

- If  $\rho_{i+1}(kT_1) \geq (1 + \delta_+) \rho_c$ , where  $\delta_+$  is a positive design parameter,  $C_i = 1$  (active);
- If  $\rho_{i+1}(kT_1) \leq (1 + \delta_-) \rho_c$ , where  $\delta_-$  is a negative design parameter,  $C_i = 0$  (inactive);
- Otherwise,  $C_i$  maintains the previous cycle status.

After doing the verification, if the variable  $C_i$  was 0 (controller inactive) in the previous time and now it is 1 (controller is activated) the new speed limit is calculated as follows:

$$V_i(kT_1) = \begin{cases} V_{i+1}((k-1)T_1) + C_v, & \text{if } \overline{V}_i(kT_1) \geq V_{i+1}(kT_1) + C_v \\ \overline{V}_i(kT_1) = f(\rho_{i+1}(kT_1)v_{i+1}(knT_1)), & \text{otherwise} \end{cases} \quad (2)$$

where  $C_v$  is a positive constant that represents the maximally allowed change of the speed limit.

The SPSC controller is implemented into the VISSIM simulation by using the VISSIM-Matlab connection. That means the same Matlab code, which

was used for simulating the mentioned models in the previous chapters, is used now for implementing the SPSC. Of course, some code lines had to be added for imposing all of the steps of the presented SPSC implementation process. Furthermore, it is necessary to define some parameters before applying this controller, such as ' $\delta+$ ', ' $\delta-$ ', maximum speed limit change ( $C_v$ ), maximum speed limit value ( $V_{max}$ ) and minimum speed limit value ( $V_{min}$ ). Such parameters configuration for this work can be found in Tab. 10.

Table 10 - Parameters configuration for the SPSC implementation.

Configuration	
Parameter	Value
$\delta+$	0.25
$\delta-$	0.15
$C_v$	20
$V_{max}$	130
$V_{min}$	60

## 5.2. Mainline Virtual Metering

The MVM controller is based on the concept of ramp metering, which, basically, reduces congestion on the highway by limiting the on-ramp inflow. The main idea of this control law can be represented by the Eq. 3.

$$R(kT_1) = R((k-1)T_1) + K_r [O_d - O(kT_1)] \quad (2)$$

where  $k$  is the time step,  $T_1$  is the discretization time,  $R((k-1)T_1)$  is the ramp metering command from the previous time step,  $K_r$  is a control parameter,  $O(kT_1)$  the measured downstream occupancy in the current step time, and  $O_d$  is the desired value for the downstream occupancy (typically close to the critical value).

This law can be generalized to regulate the metered flow rate  $Q_i$  from highway section  $(i-1)$  to  $i$ . This generalization creates a speed limit control based on the fundamental flow-density relationship, where the desired flow rate  $Q_i$  can be obtained from the following inequalities:

$$Q_1(kT_1) = \begin{cases} Q_{max}, & \text{if } \bar{Q}_i(kT_1) \geq Q_{max} \\ Q_{min}, & \text{if } \bar{Q}_i(kT_1) \leq Q_{min} \\ \bar{Q}_i, & \text{otherwise} \end{cases} \quad (3)$$



Besides that, the Equation 5 is responsible for regulating the flow at a section of the highway:

$$\overline{Q}_i(kT_1) = Q_i((k-1)T_1) + K_v \sum_{m=1}^{N_c} [\rho_d - \rho_{i+1}((k-1)N_c T_o + mT_o)] \quad (5)$$

where  $K_v$  is the controller parameter,  $\rho_i$  is the density on the section in question and  $\rho_d$  is the desired density.

The main idea presented when explaining the SPSC appears also here. When the controller is inactive, the desired speed limit change its default speed limit and when the controller is active the new speed limit value is calculated by the following equation:

$$\overline{V}_i(kT_i) = f(Q_i(kT_i)) \quad (4)$$

It is good to mention that the function  $f(Q)$  is based on the estimated flow-density relationship, which can be represented by the Eq. 7.

$$q = \rho V_f \exp\left[-\frac{1}{\alpha} \left(\frac{\rho}{\rho_c}\right)^\alpha\right] \quad (5)$$

where  $V_f$  is the free flow speed,  $\rho_c$  is the critical density, and  $\alpha$  is a parameter estimated using real traffic data.

Finally, the last step for this controller is checking if the new speed limit value generates a safe change. That means, as it was done for the SPSC case, it is necessary to certify that the new value for the speed limit is under the acceptable values. The verification is done by using the Eq. 8.

$$V_i(kT_1) = \begin{cases} V_i((k-1)T_1) - C_v, & \text{if } \overline{V}_i(kT_1) \leq V_i((k-1)T_1) - C_v \\ V_{i+1}(kT_1) + C_v, & \text{if } \overline{V}_i(kT_1) \leq V_i((k-1)T_1) - C_v \\ \overline{V}_i(kT_1), & \text{otherwise} \end{cases} \quad (8)$$

The MVM controller was implemented into the VISSIM simulation by the same way as the SPSC controller. Besides that, it was also necessary to define some parameters, which are listed in Tab. 11. The function of each parameter was shown during the explanation of the procedure along this chapter.

**Table 11 - Parameters configuration for the MVM implementation.**

Configuration	
Parameter	Value
Qmax	2500
Qmin	1600
Kv	4.5
Vmax	130
Vmin	60
Cv	20

### **5.3. VSL controller based on fuzzy logic**

The third controller is based on fuzzy logic used in rules to decide about the appropriate speed limit value. To alleviate the understanding of the working concept of this controller, basics of fuzzy logic will be explained first followed with the description of the controller.

#### **5.3.1. Basics of fuzzy logic**

Basically, fuzzy logic is a computational paradigm that is based on how the human people think. That means, the fuzzy logic looks at the world in imprecise terms and replies with precise actions, which is an attempt to combine the way how the human brain can reason (uncertainties) and the way how the machines can reason (precise valuations). Therefore, the fuzzy logic paradigm is a precise problem-solving methodology, which can handle numerical data and linguistic knowledge simultaneously. This technique facilitates the control of a complicated system without knowledge of its mathematical description.

The main difference between the fuzzy logic and the classical Boole logic is that the first one considers that a statement can assume any real value between 0 and 1, which represents the degree to which an element belongs to a given set, while the second one considers that an object can assume membership value only 0 or 1.

For seeing how the fuzzy logic can be used, it is good to mention some practical examples. Firstly, regarding the engineering sector, it can be cited that this technique enables low-cost microcontrollers to perform functions traditionally performed by more powerful expensive machines, which enables lower cost products to execute advanced features. Besides that, another good example is that the NASA has studied fuzzy control for

automated space docking simulations showing that fuzzy control system can significantly reduce the fuel consumption. The easiest example is about the wash machines, where the fuzzy controllers combined with load-weight, fabric mix, and dirt sensors can set automatically the wash cycle for the best use of power, water and detergent [15].

After explaining the main idea about fuzzy logic, it is possible to conclude what is the advantages of this system. Using fuzzy logic, development and implementation of much simpler controller without the need for intricate mathematical models (only a practical understanding of the overall system behavior) is possible. Also, the resulting control system can result in higher accuracy and smoother control as well.

### 5.3.2. Fuzzy Inference Process

The Fuzzy Inference Process represents the whole process of creation of a fuzzy logic system. Basically, it consists of three stages, which are organized in the following block scheme (see Fig. 29): Fuzzification, Rule Evaluation, and Defuzzification.

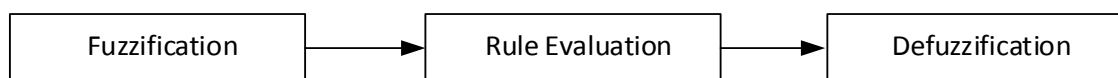


Figure 29 - Fuzzy inference process.

Each stage has its own function, which is listed below:

- **Fuzzification:** it is responsible for translating the input into truth values. In this stage, to the input variables degrees of membership are assigned. That means, the purpose is to map the inputs from a set of sensors (or features/measurements of those sensors) to values from 0 to 1 using a set of input membership functions.
- **Rule Evaluation:** it is responsible for computing the output truth values. For this, the inputs are applied to a set of “if/then” control rules and, then, the results are summed together to generate a set of fuzzy outputs.

- Defuzzification: it is responsible for transferring truth values into outputs. In this stage, the fuzzy outputs are combined into discrete values needed to drive the control mechanism.

Therefore, for the creation of a fuzzy inference process, it is necessary to follow the following steps:

1. Determining a set of fuzzy rules;
2. 'Fuzzifying' the inputs using the input membership functions;
3. Combining the fuzzified inputs according to the fuzzy rules to establish a rule strength;
4. Finding the consequence of the rule by combining the rule strength and the output membership function;
5. Combining the consequences to get an output distribution;
6. Defuzzifying the output distribution if a crisp output is needed.

### **5.3.3. Implementation of the controller**

This fuzzy logic process can be applied to the simulated models as a controller. Such implementation may be done by using the Matlab fuzzy logic toolbox. That means that the mentioned simulation framework, which enables to make the VISSIM-Matlab connection, is useful again. All of the needed stages for completing a Fuzzy Inference Process is configured in this Matlab toolbox and the VISSIM simulation is controlled by a variable speed limit controller based on fuzzy logic.

The difference between the two previously mentioned controllers and the controller in question is that in the last two controllers the speed limits are determined based on pre-specified threshold values for flow, density, and average speed, while this controller can set it up according to a combination of rules as it was explained above in the "Rule Evaluation" stage. Therefore, the rules used for the implementation of this controller into the two mentioned periods (morning period and noon period) are listed below. It is good to mention that the rules may have different weights because one of the rules can imply into the result more than another one [15].

1. If (Flow is low) then (Speed Limit is high) – Weight: 1;
2. If (Flow is medium) then (Speed Limit is medium) – Weight: 1;

3. If (Flow is high) then (Speed Limit is low) – Weight: 2;

4. If (Density is high) then (Speed Limit is low) – Weight: 2.

The mentioned Matlab toolbox is based on the three mentioned stages (Fuzzification, Rule Evaluation and Defuzzification). That means it is necessary to define each membership function for each input variable and each output variable. Of course, the membership functions will be adjusted according to the situation, which means that the membership functions for the implementation regarding the morning period will be a little different than the implementation regarding the noon period. Therefore, each membership function for the morning period, which was used for such implementation is shown in Figs. 30-32 and its parameters are organized in Tab. 12. Following the same way, each membership function for the noon period, which was used for such implementation is shown in Figs. 33-35 and its parameters are organized in Tab. 13.

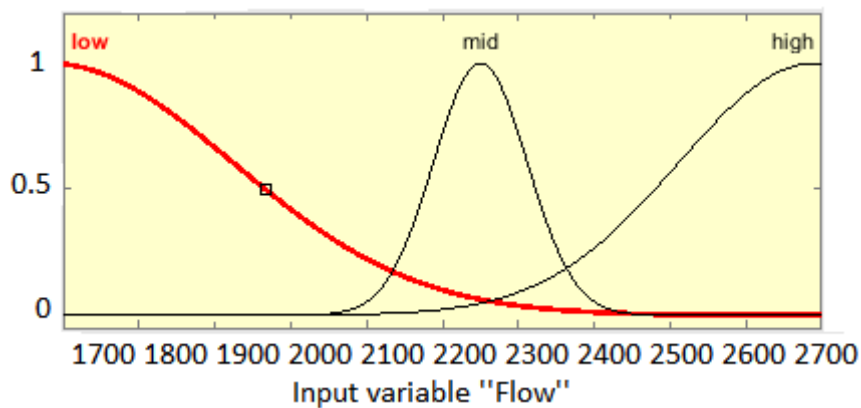


Figure 30 - Membership function shape regarding the input variable Flow (morning period).

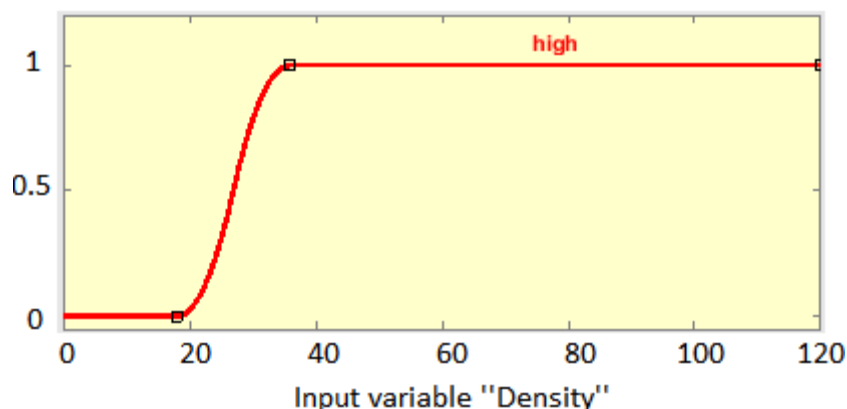


Figure 31 - Membership function shape regarding the input variable Density (morning period).

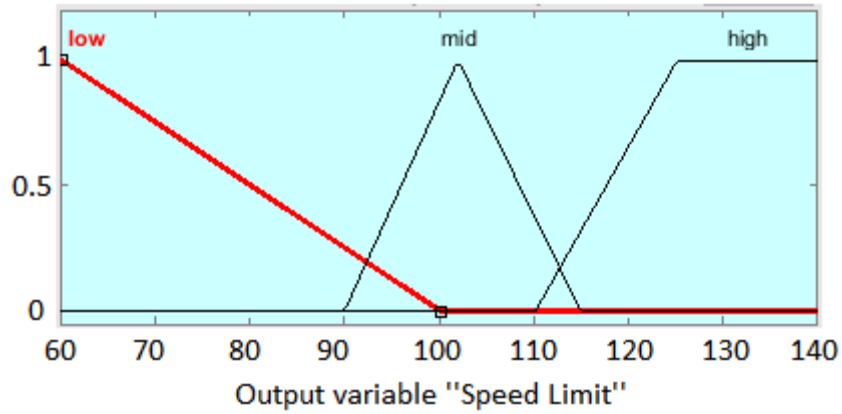


Figure 32 - Membership function shape regarding the output variable Speed Limit (morning period).

Table 12 - Parameters for each variable and class of membership function (morning period).

Variable	Class	Type	Parameters
Flow	Low	Gauss	[241.5 1682]
	Medium	Gauss	[61.9 2260]
	High	Gauss	[178.3 2690]
Density	High	Polynomial	[18 35.9 120 170]
Speed Limit	Low	Triangular	[12 60.2 100.2]
	Medium	Triangular	[90 102 115]
	High	Trapezoidal	[110.2 125.2 151.2 180.2]

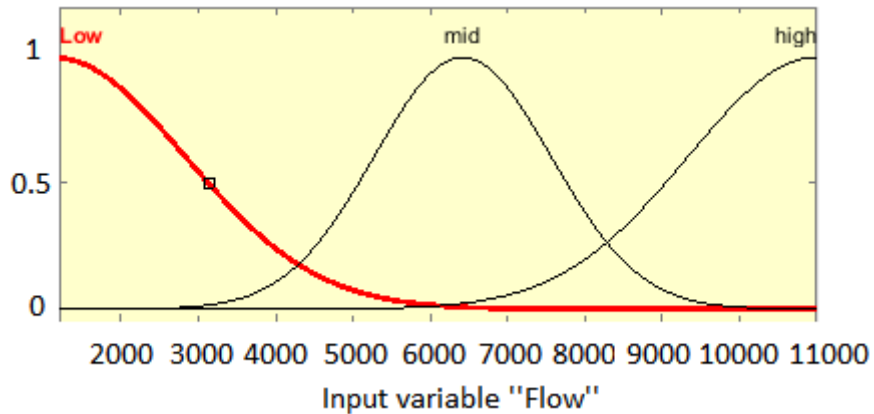


Figure 33 - Membership function shape regarding the input variable Flow (noon period).

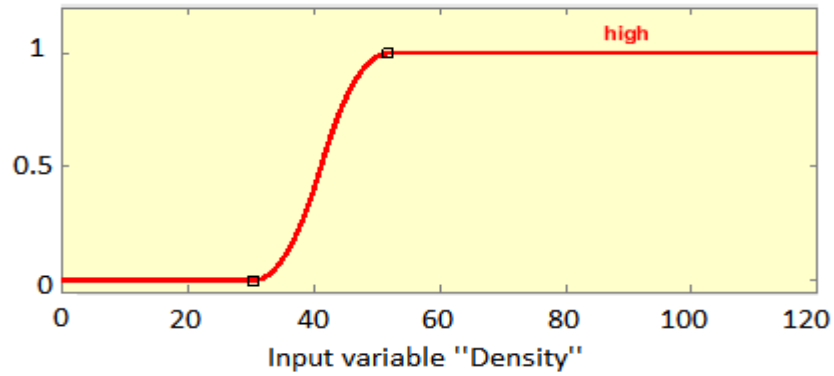


Figure 34 - Membership function shape regarding the input variable Density (noon period).

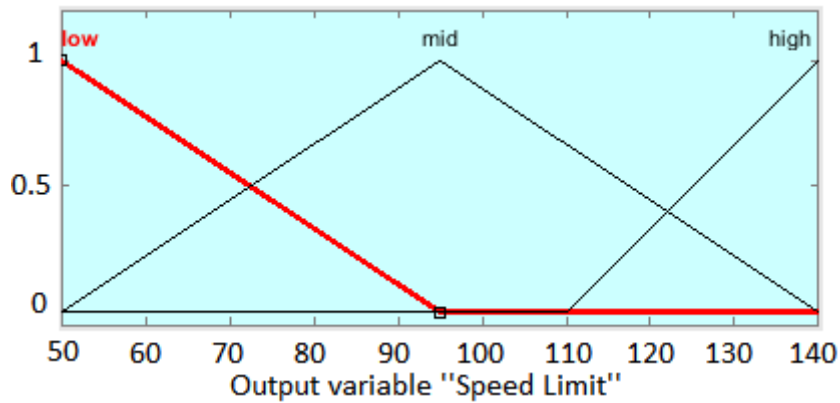


Figure 35 - Membership function shape regarding the output variable Speed Limit (noon period).

Table 13 - Parameters for each variable and class of membership function (noon period).

Variable	Class	Type	Parameters
Flow	Low	Gauss	[1703 1127]
	Medium	Gauss	[1144 6419]
	High	Gauss	[1665 11000]
Density	High	Polynomial	[30.5 51.9 126.6 133]
Speed Limit	Low	Triangular	[14 50 95]
	Medium	Triangular	[50 95 140]
	High	Trapezoidal	[110 140 141.1 155.8]

## 6. Simulation Results

After learning how each controller considered for this Internship works, it is possible to apply it to the previously calibrated simulated models. The simulations will regard the both presented periods, from 08 to 11 am (morning period) and from 12 to 14 pm (noon period) of the first August day in 2016. The main objective is comparing all of these controllers and analyzing which one has the best improvements. In order to do that, the main used comparison aspects will be TTS, TT, the queue on on-ramps, delay, the implication of the controller on the density values and emission results. Since, for this, many graphs involving all of the situations will be presented, the following relation will be considered for representing each controller:

Table 14 - Relation color-controller.

Color	Situation
Red	No VSLC
Light Green	SPSC
Light Blue	MVM
Black	FL

### 6.1. Shorter segment

The first controller implementation was done for the presented shorter segment. The controllers were applied to the same cells all the time. That means the controlled areas were the same for all simulations regarding the shorter segment in order to become a good comparison later. Therefore, the cells 1 and 5 were the chosen areas for being under control and the results are presented in continuation.

#### 6.1.1. Morning period

The analysis of this period was not planned in the beginning of the Internship. That means the first idea was to analyze only one period, which would be the noon period. However, due to the fact that the noon period is marked by constant congestions and such condition does not enable significant reactions of the controllers, the period from 08 to 11 am was chosen to see more clearly the influence of each controller. Indeed, the distinction among the involved controllers was easier, as it can be seen in the following results.

For becoming easier to examine the results, figures containing density graphs, average speed graphs, and flow graphs were created. Those figures seek to show the results for the controlled cell, besides showing the



results for the consecutive cell, since the controller can act in both. Therefore, it is possible to see in Fig. 36 how the controller acted in the first controlled area and in Fig. 37 how the controller acted in the second controlled area.

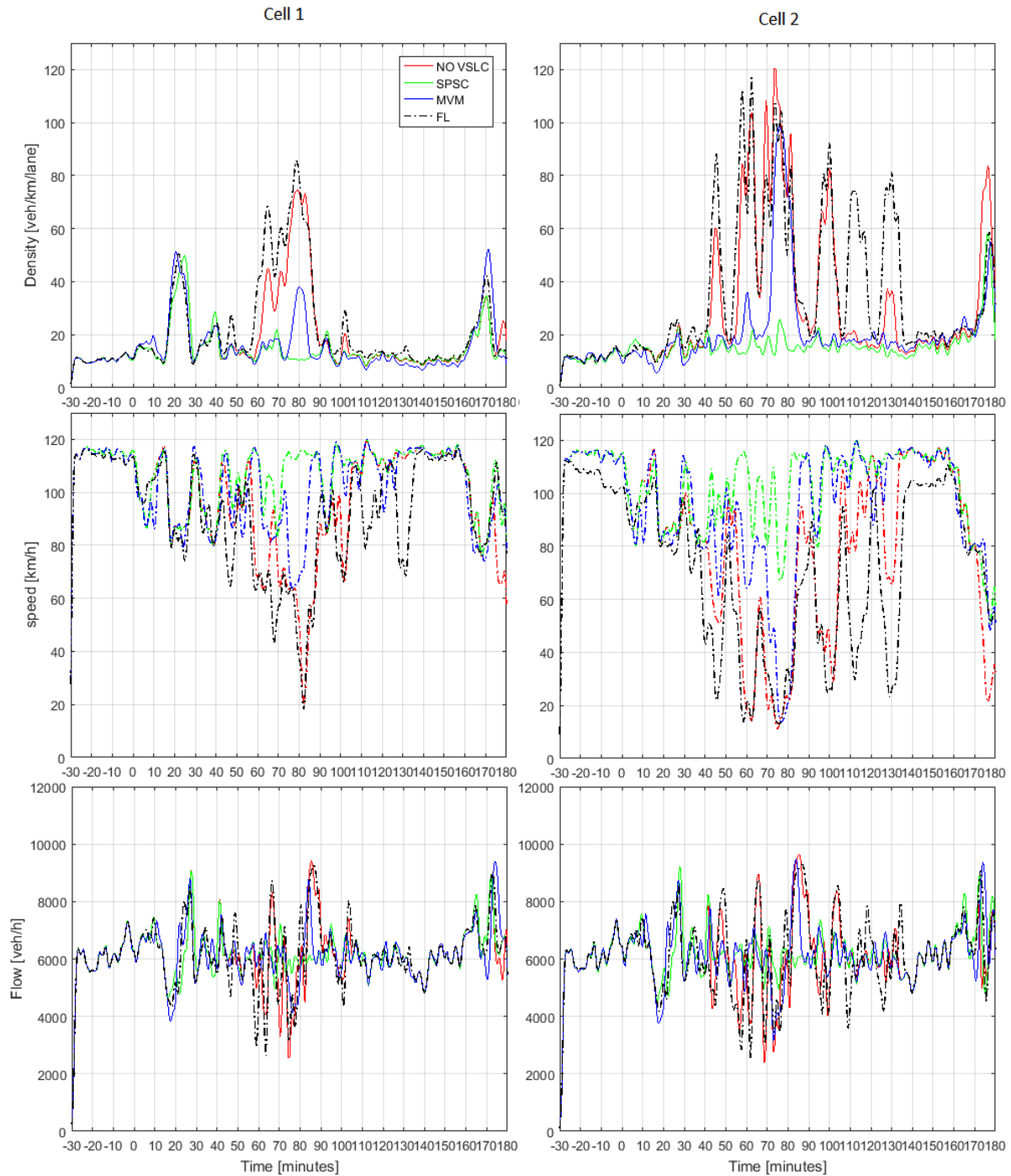
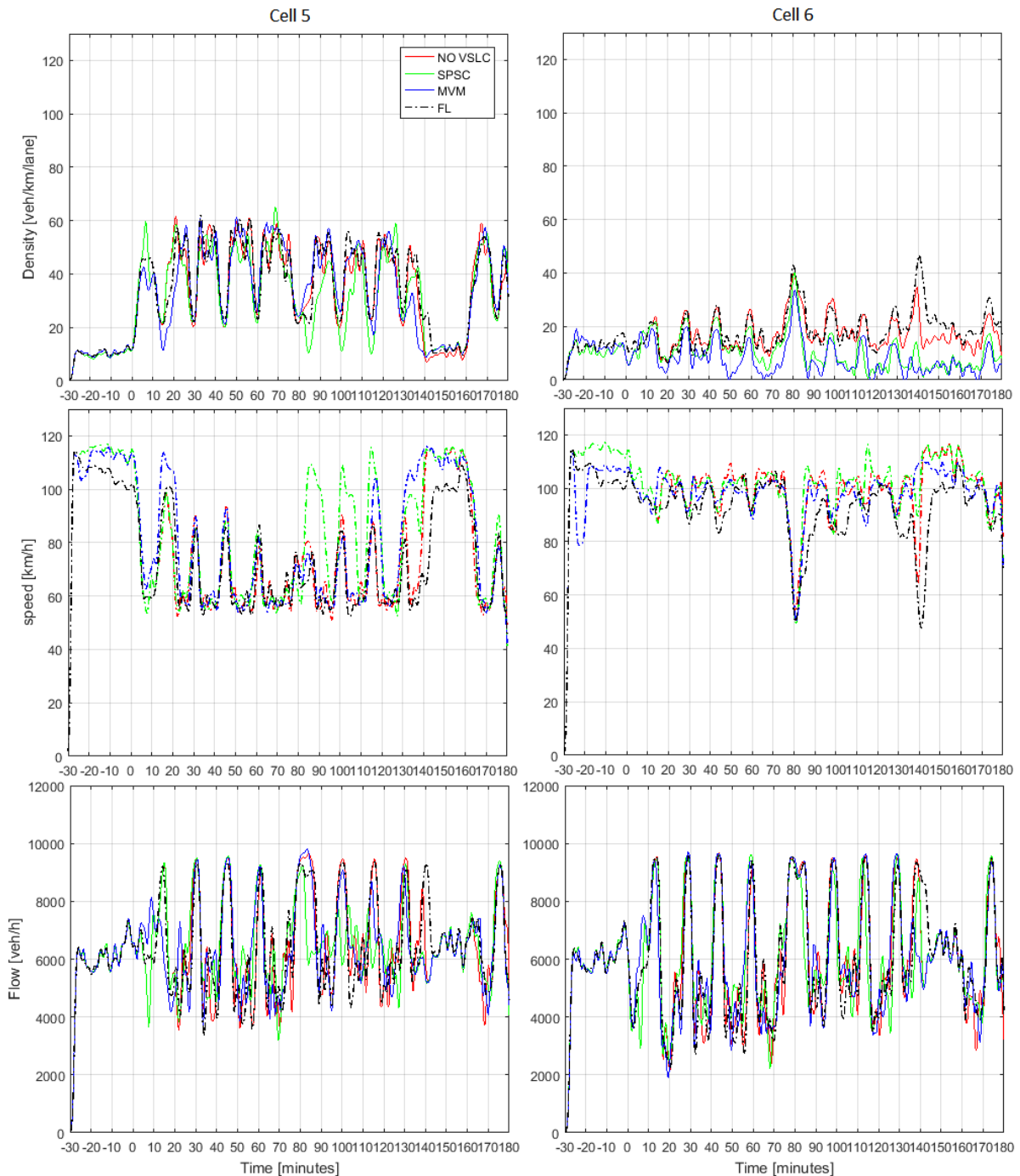


Figure 36 - Obtained density, average speed and flow for the first controlled area.



**Figure 37 - Obtained density, average speed and flow for the second controlled area.**

Confirming what was mentioned, the controller reaction is evident when it does not come to a period that is always congested. For example, in the cell 1, the comparison between the four situations shows that the only one, which did not result in improvements was the controller based on fuzzy logic. By another side, the SPSC and MVM controllers acted sharply reducing the density values from high values to acceptable values. Such reaction happened exactly when it was necessary to avoid a congestion (see Fig. 38), which is the main goal of these controllers. In the same way,

the controllers SPSC and MVM acted in the second cell reducing the density values, while the controller based on fuzzy logic kept bad results (see Fig. 39). This analysis shows that the controller based on fuzzy logic is not good for acting in the current traffic situation and the SPSC controller reduces the density values more than the MVM controller. One has to consider here that the rule settings of the fuzzy logic controller was done manually and better results can be expected with fine tuning of the fuzzy rules.

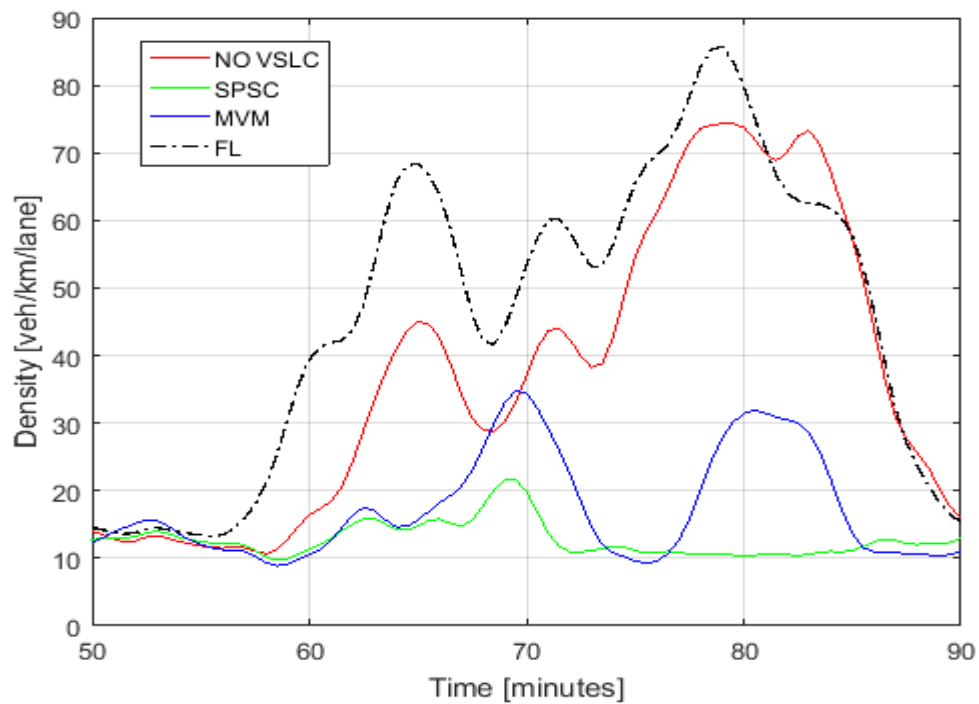


Figure 38 – Controllers reaction on the Cell 1.

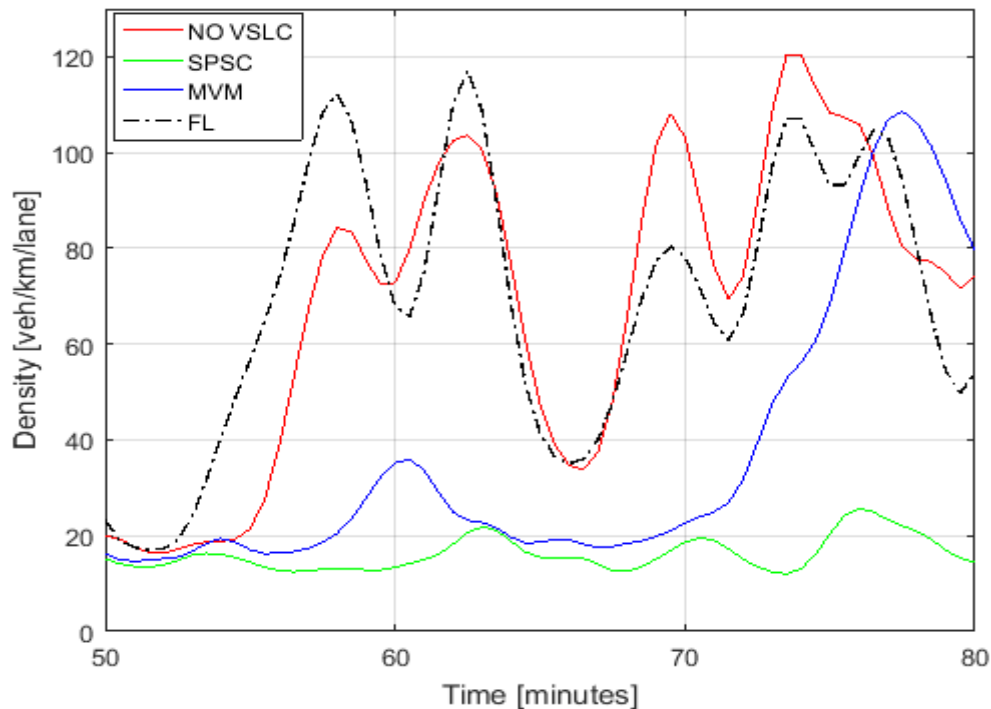
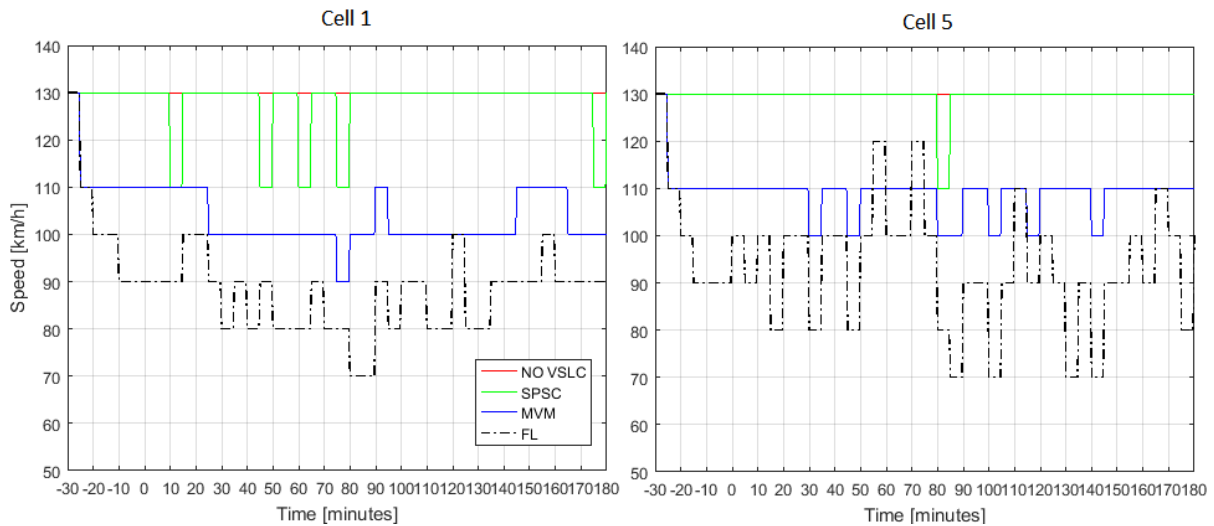


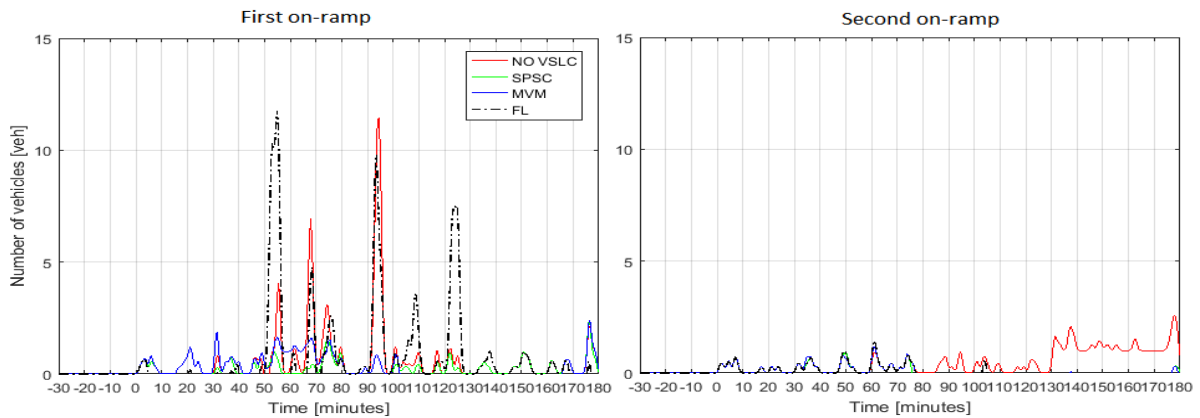
Figure 39 – Controllers reaction on the Cell 2.

Analyzing the second controlled area, the controller reaction is concentrated in the sixth cell. The controllers, except that one based on fuzzy logic, acted reducing the density values most of the time, which enabled an increase into the average speed during the simulation (look at the second graph of the second column in Fig. 37). This fact helps to get the speed homogenization and, at the same time, it enables to travel faster. Besides that, the speed homogenization can cause the emissions reduction, showing that the controllers are achieving the objectives.

Now, it is important to show how the speed limit changed during the simulation as the controllers were acting (see Fig. 40). It is possible to see that the changes are not constant because it comes to a period not marked by congestions. Furthermore, it is important to analyze what is the influence of the controllers on the queue lengths. That is the reason for showing those graphs in Fig. 41. It is evident that the controllers acted reducing the queue lengths most of the time, except the fuzzy logic controller, which increases the queue length in the first on-ramp. This increase happens because such controller causes significant reductions of the speed limits in the mainstream as it is shown in Fig. 40. That means the vehicles travel slower in the mainstream making the queue longer on the first on-ramp when it comes to the controller based on fuzzy logic.



**Figure 40 - Speed limit changes during the simulation due to the controller's reaction.**



**Figure 41 - Queue lengths on the on-ramps during the simulation.**

Finally, for this case, it is good to make a quantitative analysis for seeing how the average and maximal values changed after applying the controllers. For this, the Tab. 15 was built comparing the non-controlled situation with all of the controlled situations and it was considered TT, TTS, delay, and queue length values as parameters of comparison. This numeric comparison makes it possible to see that the controller based on fuzzy logic, in fact, does not cause improvements as it was mentioned. By the other side, the SPSC and the MVM have caused some improvements, but, in this comparison, it is possible to see that the MVM is more efficient, contrary to what was shown in the graph analysis, where the SPSC controller looked more efficient.

Table 15 - Quantitative analysis for the shorter segment regarding the morning period.

	No VSLC	SPSC		MVM		FL	
		Obtained	Reduction [%]	Obtained	Reduction [%]	Obtained	Reduction [%]
TTS [veh·h]	1303.3	982.1	24.6	730.5	43.9	1392.3	-6.8
Average TT [s]	309.2	302.5	2.2	266.2	13.9	331.8	-7.3
Maximal TT [s]	787.2	787.2	0.0	679.1	13.7	843.4	-7.1
Average delay [s]	173.9	167.2	3.9	128.3	26.2	178.6	-2.7
Maximum delay [s]	664.5	664.5	0.0	552.5	16.9	702.5	-5.7
Average queue length [veh]	0.6	0.3	50.0	0.1	83.3	0.6	0.0
Maximal queue length [veh]	15.0	7.0	53.3	6.0	60.0	17.0	-13.3

Helping to compare the situations quantitatively, the emission results were computed by using the software EnViVeR. As previously mentioned, one of the goals of VSLC is getting lower emissions during the analyzed period. Therefore, the main idea is to see how the controllers act into the emission of exhaust gasses. That means that, it is necessary to check if the controllers are able to reduce the emissions during the period in question. This analysis will consider the following configuration (see Tab. 16), which is the same configuration used in [1], and the emission results are presented in Tab. 17.

Table 16 - Used configuration for the emission results.

Fuel type			
Petrol [%]	Diesel [%]	LPG [%]	Electric [%]
67	30.5	2.3	0.2
Vehicle age distribution			
Newer than 1 year	Average vehicle age	Average exit age	Maximum age
7.50%	7.7 years	19.0 years	40 years
Average CO2 emission			
Petrol [g/km]		Diesel [g/km]	
166		158	

Table 17 - Emission results for the shorter segment regarding the morning period.

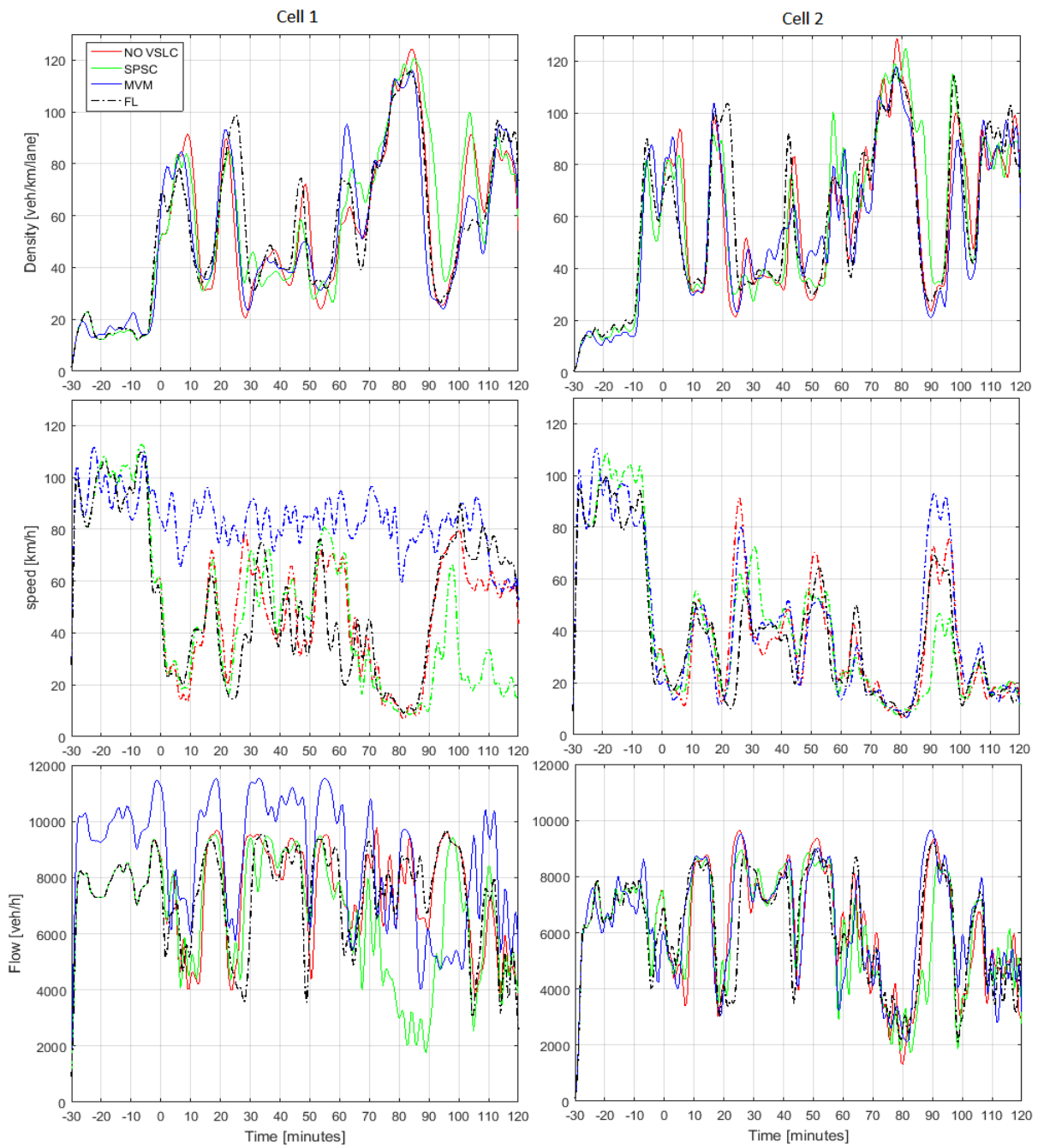
Emission type	No VSLC	SPSC		MVM		FL	
		Obtained	Red. [%]	Obtained	Red. [%]	Obtained	Red. [%]
CO <sub>2</sub>	13.43 · 10 <sup>6</sup> g	11.56 · 10 <sup>6</sup> g	13.92	11.51 · 10 <sup>6</sup> g	14.32	12.79 · 10 <sup>6</sup> g	4.8
	7.091 · 10 <sup>6</sup> g/h	6.114 · 10 <sup>6</sup> g/h	13.77	6.08 · 10 <sup>6</sup> g/h	14.3	6.775 · 10 <sup>6</sup> g/h	4.46
	240 g/km	209.04 g/km	12.9	205.9 g/km	14.21	231.1 g/km	3.7
NO <sub>x</sub>	34.3 · 10 <sup>3</sup> g	31.82 · 10 <sup>3</sup> g	7.23	31.02 · 10 <sup>3</sup> g	9.56	31.18 · 10 <sup>3</sup> g	9.1
	18.12 · 10 <sup>3</sup> g/h	16.761 · 10 <sup>3</sup> g/h	7.5	16.43 · 10 <sup>3</sup> g/h	9.3	16.62 · 10 <sup>3</sup> g/h	8.3
	0.6131 g/km	0.5671 g/km	7.5	0.5542 g/km	9.6	0.5669 g/km	7.53
PM <sub>10</sub>	2462 g	2298 g	6.65	2361 g	4.1	2381 g	3.3
	1300 g/h	1210 g/h	6.9	1240 g/h	4.6	1262 g/h	2.9
	0.044 g/km	0.04116 g/km	6.45	0.04198 g/km	4.6	0.04277 g/km	2.8

As it was mentioned, due to the reached speed homogenization, it was expected that the emission of exhaust gasses were reduced. Analyzing the Tab. 16, it is possible to confirm that, since all of the controllers caused the emissions reduction. Besides that, it is important to mention that, the controller based on fuzzy logic only showed improvements when it came to the emission results. However, that is not sufficient for achieving the objectives. That means it is possible to state that such controller can not react properly in the current traffic situation using the current rule configuration, while the SPSC and MVM controllers were able to get improvements in all of the aspects.

### 6.1.2. Noon period

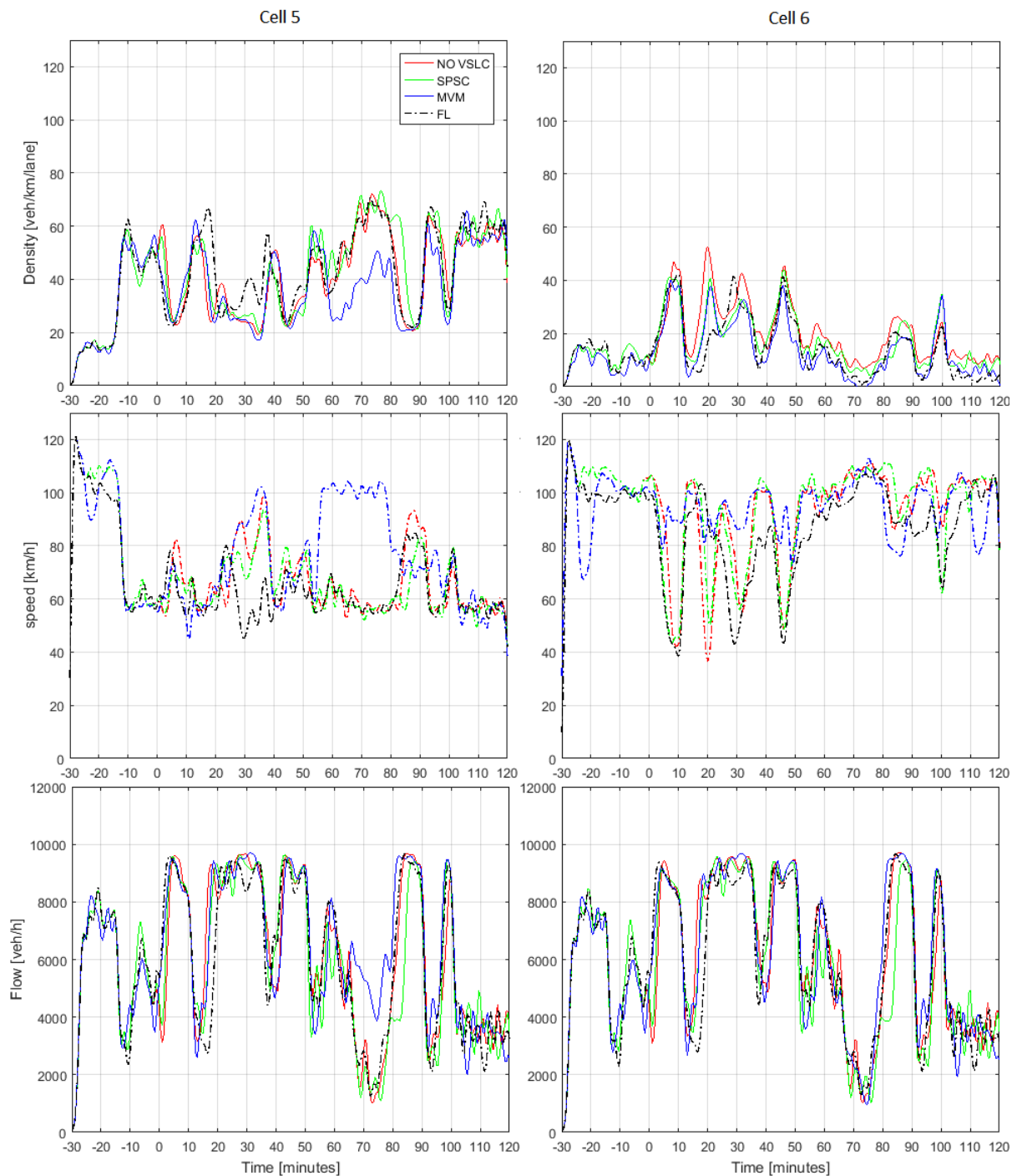
As it was mentioned, the noon period is marked by constant congestions and this fact makes harder the controller reaction. Therefore, the comparison between the controllers and the noncontrolled situation will be presented as it was done for the morning period, but the main points where the controller action can be noticed will be highlighted.

Following the same way of analysis, the graphs of density, average speed, and flow were built for the two controlled areas, including the three different types of controllers. This analysis can be seen in Figs. 42-43.



**Figure 42 - Obtained density, average speed and flow for the first controlled area.**





**Figure 43 - Obtained density, average speed and flow for the second controlled area.**

In the first controlled area, it is possible to see that the controllers can not make significant improvements. However, there is a place where two of the controllers reacted reducing the density values, while the other one did not react. This case regards the cell 1 and it is shown in Fig. 44. The SPSC controller was the only one that did not react and the controller based on fuzzy logic was the only one that has reduced the density values from critical values to acceptable values.

Besides that, the second controlled area also does not have significant influences from the controllers, but it is possible to see in the cell 6 around 15 minutes after the warm-up period that all of the controllers acted reducing the density values (see Fig. 45). For the second time, the controller based on fuzzy logic was the responsible for the biggest reduction. It is good to mention that the improvement regarding the cell 6 happened where the highest density values for this cell before the implementation were placed, which shows the controllers efficiency.

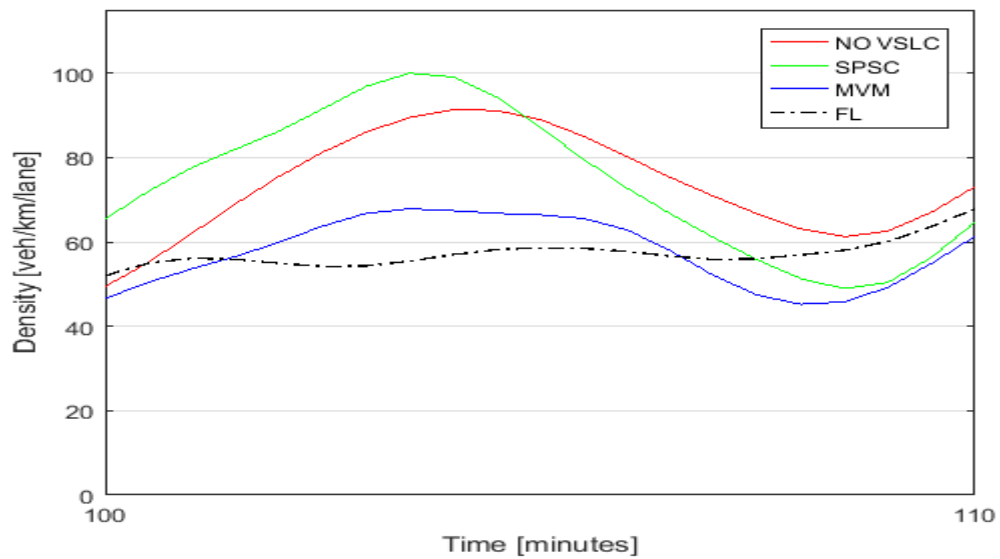


Figure 44 - Controller reaction on the cell 1.

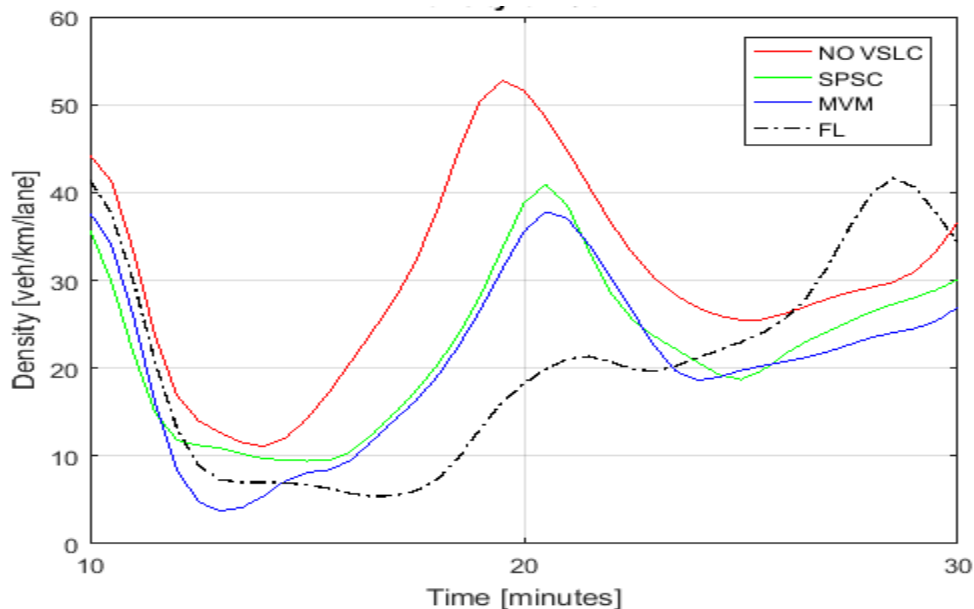


Figure 45 - Controller reaction on the cell 6.

Of course, there are some places where the controllers cause the increase of density, instead of causing the reduction of it. That means, since

there is no perfect controller, it is possible to notice in this analysis some problematic points. For example, on the cell 5 around the 50 minutes after the warm-up period (see Fig. 46), the density values regarding the controlled situations are greater than the density values regarding the noncontrolled situation.

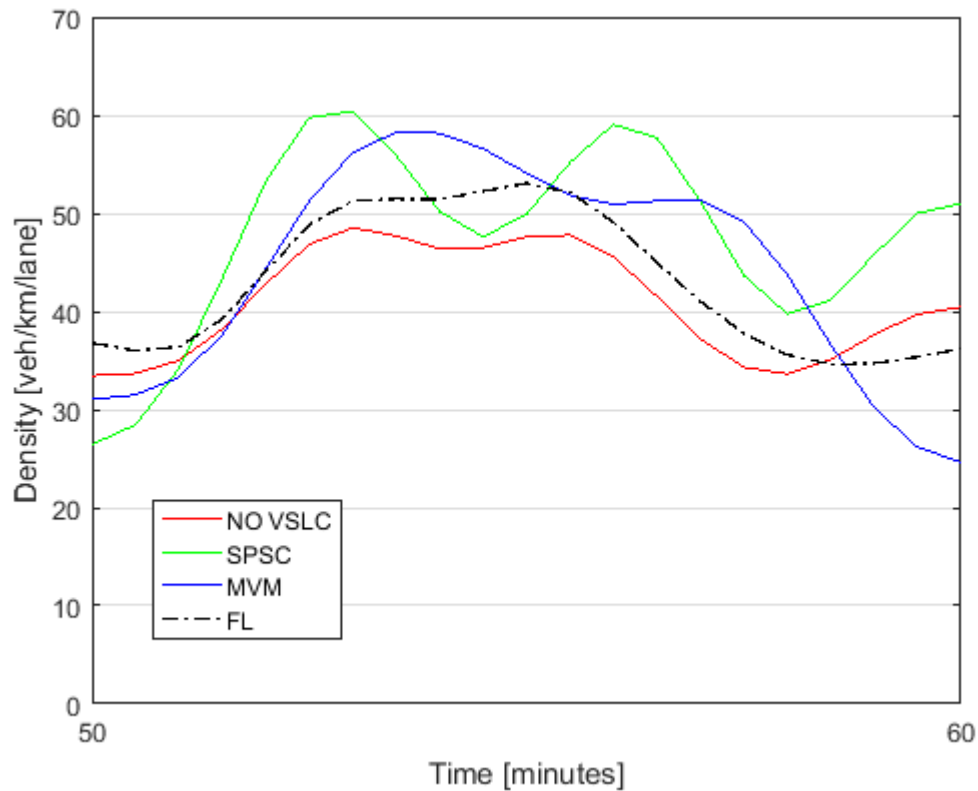
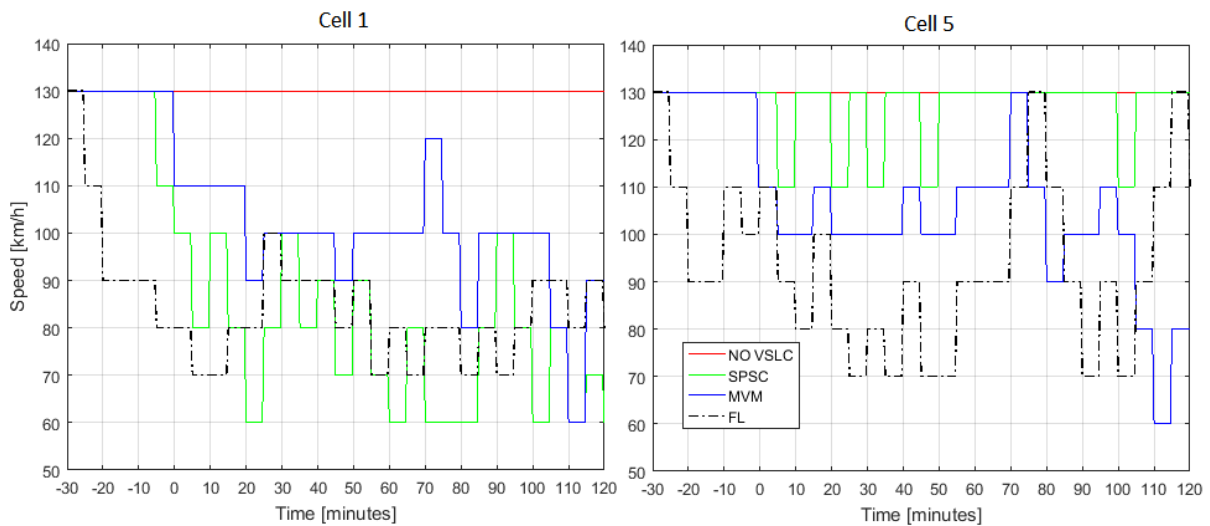
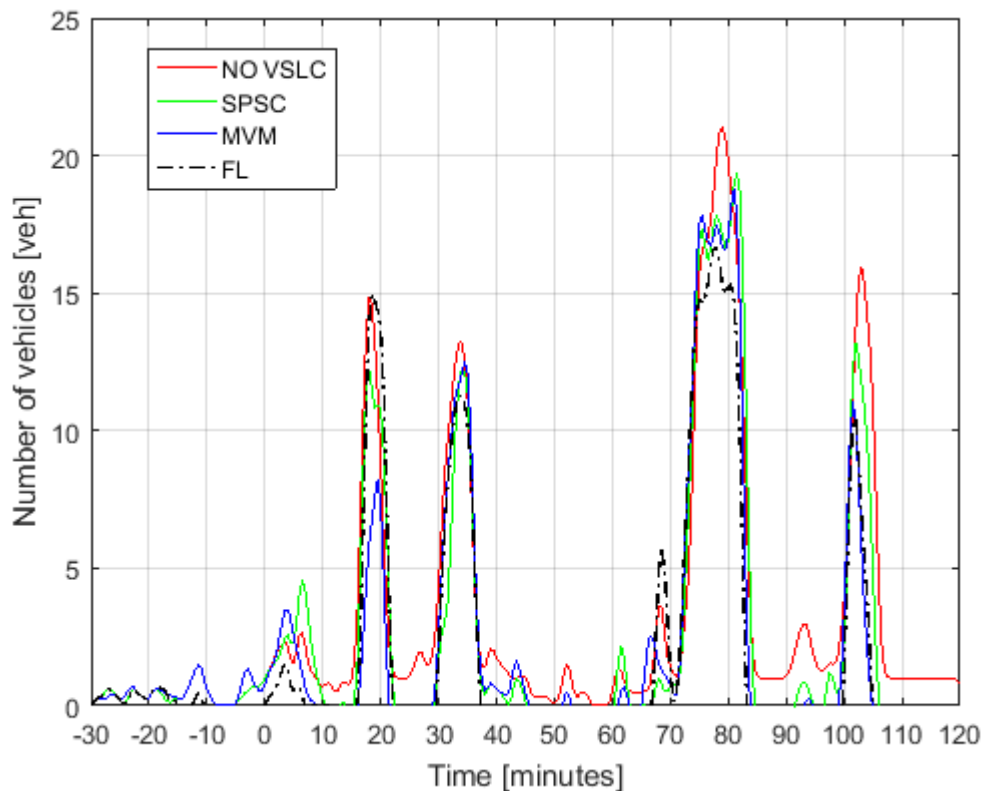


Figure 46 – A problematic point where the controllers cause an increase in the density values.

Since the controller acts by changing the speed limit during the simulation, it is necessary to analyze how these changes happened on the controlled cells (see Fig. 47). It is possible to see that the speed limit changes happens all the time because it comes to a congested period. Furthermore, the queue lengths during the simulation should be analyzed for seeing what is the influence from the controllers on them. Therefore, a graph showing the queue lengths on the first on-ramp was built (see Fig. 48) and it is clear that the controllers acted reducing this queue in the most times. The queue analysis was done only for the first on-ramp because the other ones do not have big influences from the controllers.



**Figure 47 - Speed limit changes during the simulation.**



**Figure 48 - Queue on the first on-ramp.**

After doing a graphic analysis, it is important to compare the controllers by using a quantitative analysis because it is easier to see if the controller is reacting in the general setting. In order to do that, Table 18 was built considering TTS, travel time, delay, and queue length. It is evident that the controllers reacted correctly in the most times. However, comparing the three controllers, it is possible to make some comments about that. For example, taking the TTS as the main measurement, it can be

concluded that for this case the MVM caused the best improvement. Furthermore, regarding the SPSC controller, it is possible to comment that such controller does not have notable reactions when it comes to a congested situation. And, finally, regarding the controller based on fuzzy logic it was possible to notice a good behavior on this scenario, reducing all of the average comparison parameters and showing increases only when it comes to maximum values, which is acceptable if the average value was reduced in comparison to the situation without any VSLC.

**Table 18 - Quantitative analysis regarding the shorter segment.**

	No VSLC	SPSC		MVM		FL	
		Obtained	Reduction [%]	Obtained	Reduction [%]	Obtained	Reduction [%]
<b>TTS [veh-h]</b>	1330	1328.9	0.1	1323.8	0.5	1326.9	0.23
<b>Average TT [s]</b>	522.2	517.6	0.9	508.8	2.6	518.3	0.75
<b>Maximal TT [s]</b>	1250.9	1222.8	2.2	1195	4.5	1416.3	-13.2
<b>Average delay [s]</b>	382.9	381.6	0.4	373.6	2.4	369.9	3.4
<b>Maximum delay [s]</b>	1122.3	1489	-32.7	1111	1	1260.1	-12.3
<b>Average queue length [veh]</b>	2	2.3	-15.6	1.9	3.2	2	0
<b>Maximal queue length [veh]</b>	20	22	-10	22	-10	19	5

The last important analysis, which should be done also, regards the emission results. The used configuration for getting the emission results for the noon period of the shorter segment was the same configuration used for the morning period (see Tab. 16). Therefore, using the software EnViVeR, the results were obtained and the Table 19 shows the comparison between the different controlled situations and the non-controlled situation, where it is possible to see that the controllers have reduced the emissions in the most times. The only present problem is about the SPSC controller, which did not reduce the PM10 emissions, confirming the fact that such controller does not react very well in such a scenario.

Table 19 - Emission results regarding the shorter segment (noon period).

Emission type	No VSLC	SPSC		MVM		FL	
		Obtained	Red. [%]	Obtained	Red. [%]	Obtained	Red. [%]
CO <sub>2</sub>	15.89 · 10 <sup>6</sup> g	15.31 · 10 <sup>6</sup> g	3.65	15.23 · 10 <sup>6</sup> g	4.15	14.84 · 10 <sup>6</sup> g	6.6
	8.678 · 10 <sup>6</sup> g/h	8.363 · 10 <sup>6</sup> g/h	3.63	8.32 · 10 <sup>6</sup> g/h	4.12	8.12 · 10 <sup>6</sup> g/h	6.4
	264.5 g/km	255.4 g/km	3.45	253.84 g/km	4.03	246.1 g/km	7
NO <sub>x</sub>	40.97 · 10 <sup>3</sup> g	39.81 · 10 <sup>3</sup> g	2.83	38.53 · 10 <sup>3</sup> g	5.96	38.14 · 10 <sup>3</sup> g	6.9
	22.38 · 10 <sup>3</sup> g/h	21.78 · 10 <sup>3</sup> g/h	2.67	21.27 · 10 <sup>3</sup> g/h	4.97	20.84 · 10 <sup>3</sup> g/h	6.9
	0.6823 g/km	0.6624 g/km	2.92	0.6459 g/km	5.33	0.6325 g/km	7.3
PM <sub>10</sub>	2884 g	2893 g	-0.31	2813 g	2.46	2763 g	4.2
	1575 g/h	1589 g/h	-0.89	1539 g/h	2.25	1507 g/h	4.3
	0.04802 g/km	0.04932 g/km	-0,69	0.04626 g/km	2.36	0.04604 g/km	4.12

## 6.2. Longer segment

After doing all of the previous procedure for the shorter segment, each step was done for the longer segment. For this case, the areas under control have involved the cells 1, 8 and 12.

### 6.2.1. Morning period

Firstly, the analysis will be done for the period, which is not marked by congestions. The usual comparison between the non-controlled situation and all of the controlled situations is shown in Figs. 49-51. It is possible to see in those figures the controller reaction by analyzing the density graphs exactly how it was done for the two previous presented analysis. However, in this case, there is an unexpected behavior from the SPSC controller and the analysis of such behavior is the special case in this chapter.

First of all, following the usual analysis, it is possible to show where the controllers are correctly reacting. For example, in the first controlled area, the main reaction which can be noticed is concentrated in the cell 2. In this cell, all of the controllers have reduced the density values most of the time. Regarding the second controlled area, the main noticed point is around 130

minutes after the warm-up period. In this case, the density values were extremely high and the controllers got to reduce these values, except the SPSC controller, which kept it high at this time (see Fig. 52). Analyzing the last controlled area, the controllers could react freely because the entire period is free of congestions. And, indeed, all of the controllers reduced the density values all the time.

It is important to notice that the results about the cell 8 confirm what was already mentioned. That means, when the density values are really high, the controller reaction is limited and that is why the controllers reduced the density but keeping it still out of acceptable values (see Fig. 52).

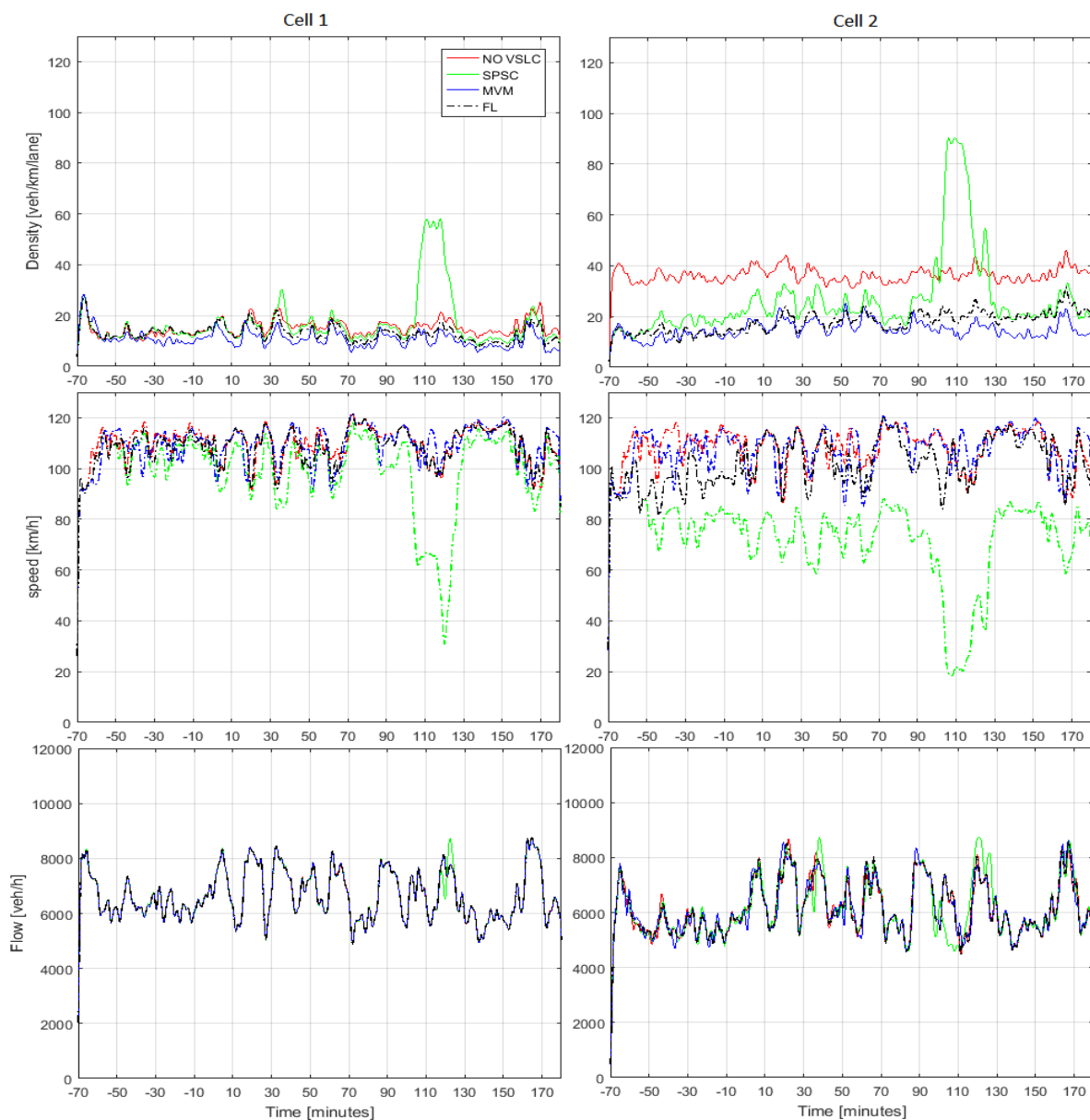
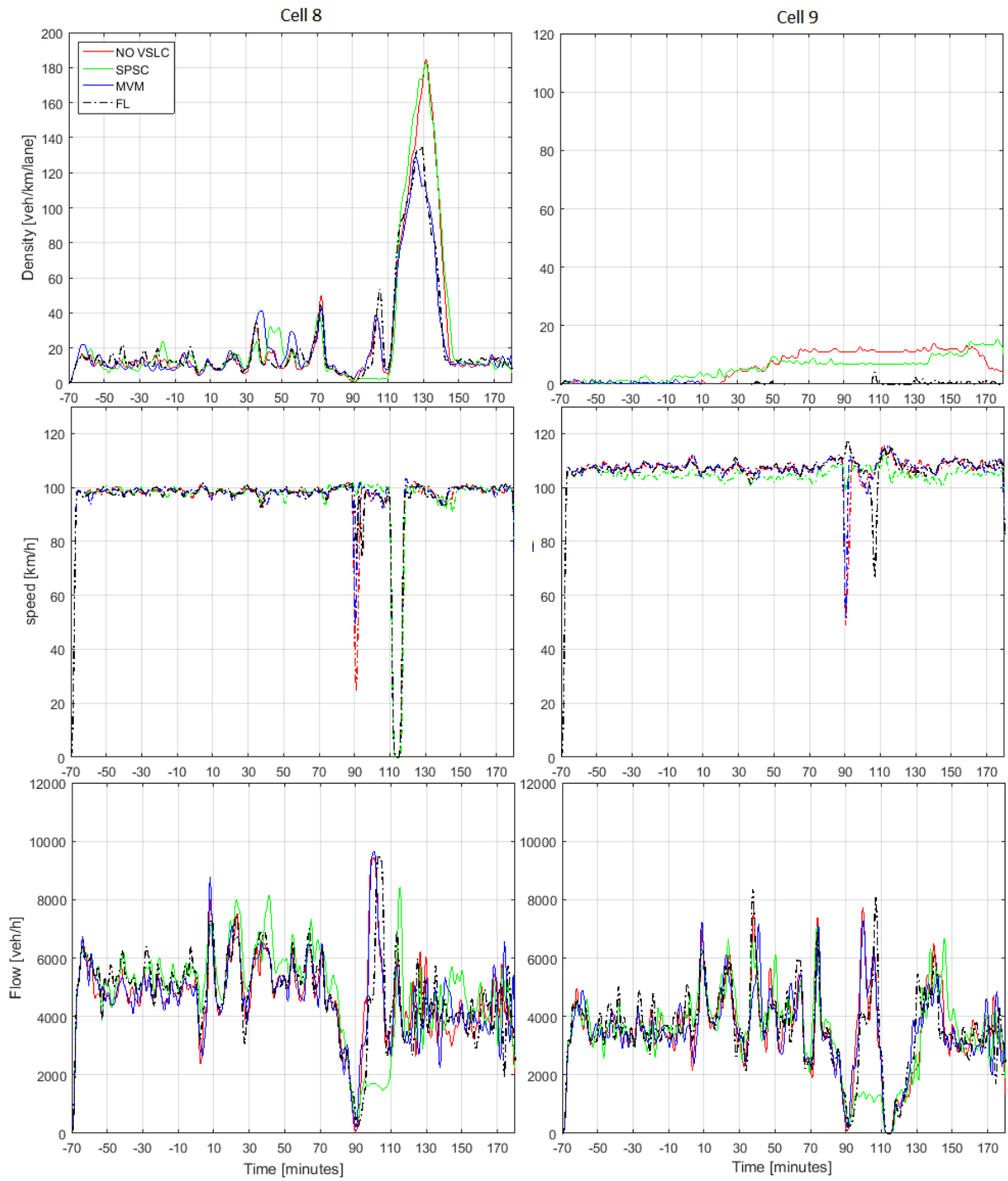
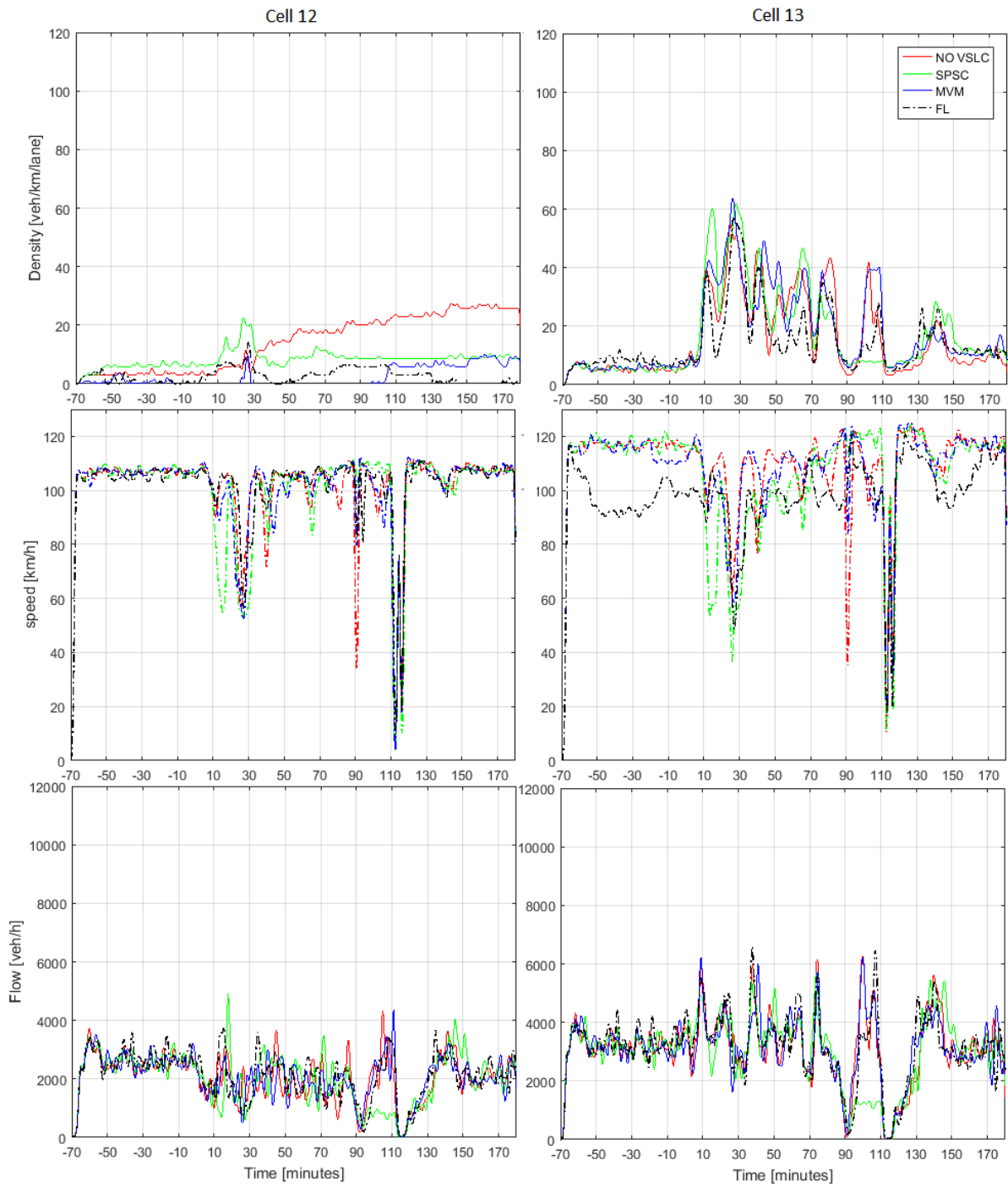


Figure 49 - Obtained density, average speed and traffic flow for the first controlled area.



**Figure 50 - Obtained density, average speed and traffic flow for the second controlled area.**





**Figure 51 - Obtained density, average speed and traffic flow for the third controlled area.**

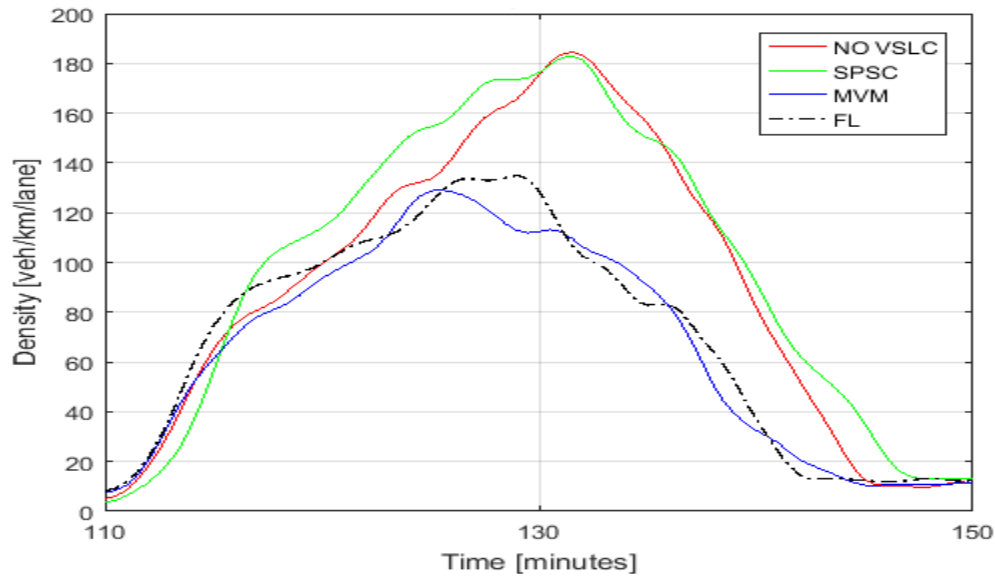


Figure 52 - Controller reaction in the second controlled area.

Focusing, now, on the different analysis which needs to be done in this chapter, it is important to comment how the SPSC controller increased the density values in the cell 1 while the other controllers showed low values for density (see Fig. 53). For explaining what can have happened in such case, it is necessary to show how the speed limit changed on the controlled cells during the simulation (see Fig. 54). Since the SPSC controller acts by changing the speed limit on the controlled cells after comparing the downstream density with the critical density, the ocured problem was that the downstream density increased at first (see the density graph in the first column of the Fig. 49) and because of this the controller reduced the speed limit forcing the vehicles reducing the speed. This reduction can have caused a congestion and, consequently, the speed limit kept low all the time in this cell what explains the high values for density shown by the SPSC line.

Furthermore, the queue lengths also need to be analyzed. The Fig. 55 shows how the controllers acted into this aspect. It is clear that all of the controllers reduced the queue on the first on-ramp all the time. However, it is important to mention that the MVM controller was that one which got the shortest queues for this case. The others on-ramps are not shown here because there is no big difference between the situations.

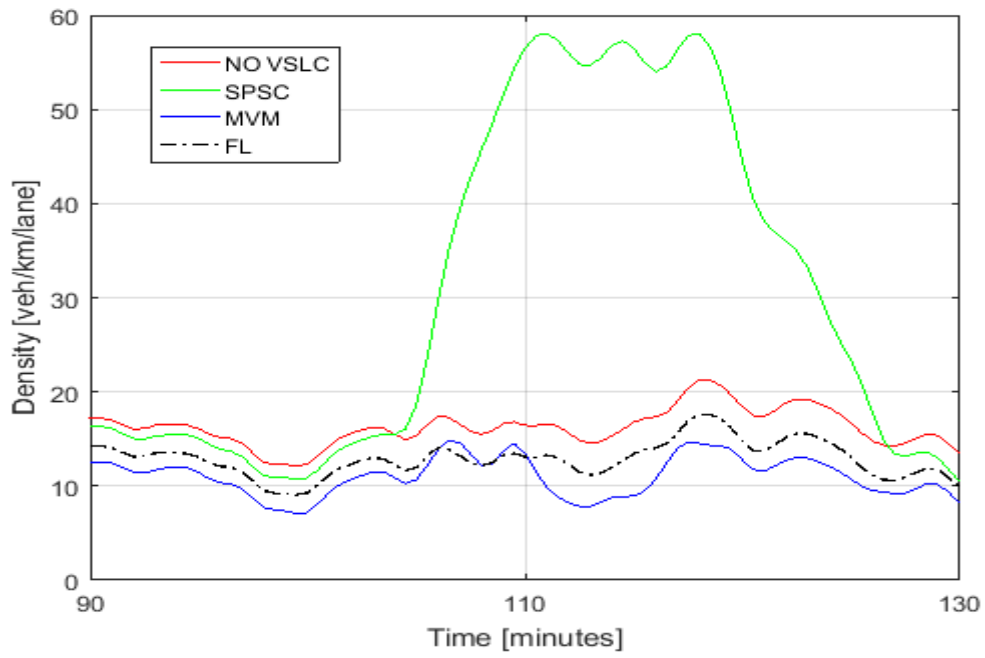


Figure 53 - Unexpected behavior from the SPSC controller.

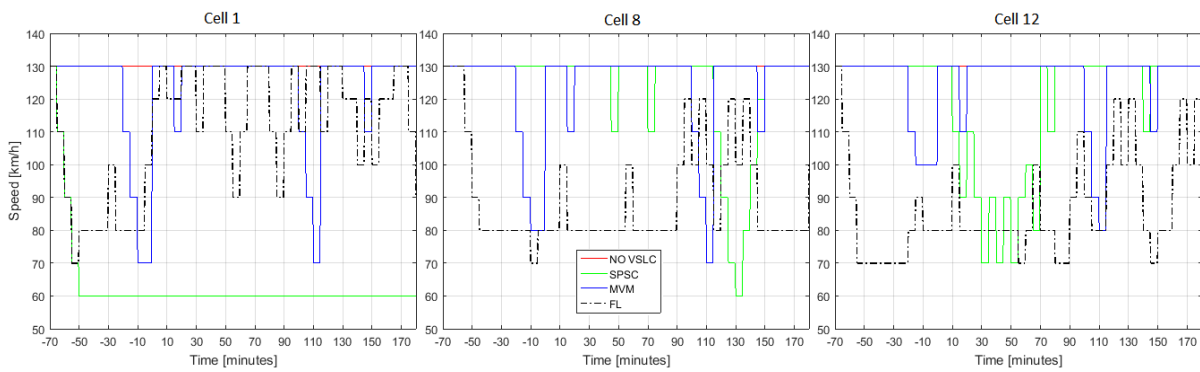


Figure 54 - Speed limit changes on the controlled cells during the simulation.

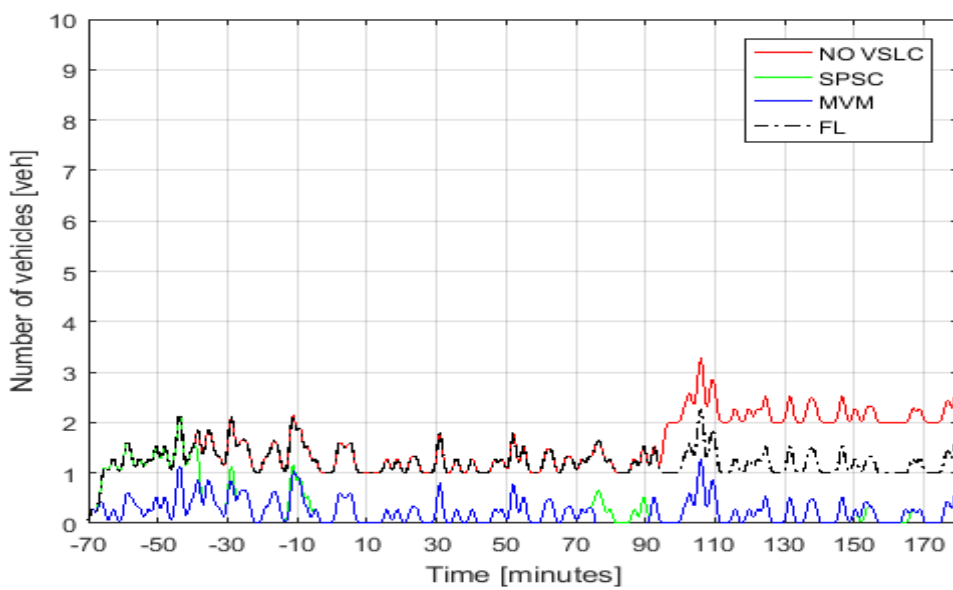


Figure 55 - Queue lengths on the first on-ramp.

Finally, the quantitative analysis regarding the TT, TTS, delay and queue length was done and it is shown in Tab. 20. Besides that, using the same mentioned EnViVeR configuration, the emission results were computed also and they can be found in Tab. 21.

It is possible to see that, regarding the traffic parameters, two of the controllers reacted correctly (MVM and fuzzy logic controller) reducing the average values in relation to the noncontrolled situation. That means the MVM controller and the controller based on fuzzy logic resulted in improvements in all of the aspects, except when it comes to the average delay, which was increased for the MVM case. It is good to mention when only one of the comparison parameters is showing bad results does not mean that the controller is not reacting. It can happen because it does not exist perfect controller.

By other side, while those two controllers reacted correctly, the SPSC controller did not show significant improvements. As it can be seen in Tab. 20, the only comparison parameter, for which the SPSC controller acted resulting in improvements regarding the queue length, showing that the graph analysis was right done, since when the results were shown in graphs, the only case that the SPSC got better results regarded the queue lengths. It is also possible to state that the reason for bad results in the quantitative comparison is the fact that the SPSC controller had that mentioned unexpected behavior.

The same analysis can be done for the emission results. It is clear in Tab. 21 that all of the controllers reduce the emission of exhaust gasses for the current traffic situation, which proves that the controllers reached one of the main goals of such type of controller.

**Table 20 - Quantitative analysis for the longer segment regarding the morning period.**

	No VSLC	SPSC		MVM		FL	
		Obtained	Red [%]	Obtained	Red [%]	Obtained	Red [%]
<b>TTS [veh·h]</b>	16415.1	16367.8	0.3	14396.0	12.3	15760.8	4.0
<b>Average TT [s]</b>	419.7	425.5	-1.4	403.3	3.9	357.7	14.8
<b>Maximal TT [s]</b>	2908.5	3312.0	-13.9	1654.4	43.1	1680.1	42.2
<b>Average delay [s]</b>	146.7	163.5	-11.4	189.5	-29.2	108.2	26.3
<b>Maximum delay [s]</b>	2615.3	3005.7	-14.9	1371.4	47.6	1483.7	43.3
<b>Average queue length [veh]</b>	1.6	0.4	76.8	0.2	87.4	1.2	21.6
<b>Maximal queue length [veh]</b>	5.0	4.0	20.0	3.0	40.0	4.0	20.0

Table 21 - Emission results for the longer segment regarding the morning period.

Emission type	No VSLC	SPSC		MVM		FL	
		Obtained	Red. [%]	Obtained	Red. [%]	Obtained	Red. [%]
CO <sub>2</sub>	16.26 · 10 <sup>6</sup> g	15.24 · 10 <sup>6</sup> g	6.3	15.56 · 10 <sup>6</sup> g	4.3	15.72 · 10 <sup>6</sup> g	3.3
	6.92 · 10 <sup>6</sup> g/h	6.48 · 10 <sup>6</sup> g/h	6.4	6.62 · 10 <sup>6</sup> g/h	4.3	6.71 · 10 <sup>6</sup> g/h	3.1
	213.2 g/km	199.6 g/km	6.4	204.0 g/km	4.3	206.0 g/km	3.4
NO <sub>x</sub>	40.22 · 10 <sup>3</sup> g	39.62 · 10 <sup>3</sup> g	1.5	30.05 · 10 <sup>3</sup> g	5.4	39.70 · 10 <sup>3</sup> g	1.3
	17.11 · 10 <sup>3</sup> g/h	16.85 · 10 <sup>3</sup> g/h	1.5	16.13 · 10 <sup>3</sup> g/h	5.7	16.90 · 10 <sup>3</sup> g/h	1.2
	0.5275 g/km	0.5196 g/km	1.5	0.4958 g/km	6	0.5206 g/km	1.3
PM <sub>10</sub>	3038 g	2819 g	7.2	2971 g	2.2	3011 g	0.9
	1293 g/h	1204 g/h	6.92	1265 g/h	2.2	1279 g/h	1.1
	0.03984 g/km	0.03713 g/km	6.8	0.03896 g/km	2.2	0.03956 g/km	0.7

### 6.2.2. Noon period

The other implementation, which was done for the longer segment regards the noon period. As it was mentioned, the controller reaction is limited in this case due to the fact that is a period marked by congestions. Even so, the controllers were able to make some improvements, which will be highlighted in this chapter. Of course, there are some problematic points where the controllers did not react and such cases also will be highlighted here. For this analysis, all of the results for each controlled area is shown in Figs. 56-58.

As it is possible to see, in the first controlled area the controllers did not show significant differences between the non-controlled situation and the controlled situations. The only case where the controllers made the density values lower regards the cell 2, where the controllers acted all the time, except the SPSC controller, which did not react in this case. The non-reaction of the SPSC controller in the current situation is not a big deal because the density values are low and the controller, at least, kept those low values most of the time. Therefore, the problem is concentrated in the last 20 minutes of the cell 2, when such controller increases the density values to values close to critical values.

In the second controlled area the main points of reaction are located. For example, around 30 minutes after the warm-up period, all of the controllers got to reduce the density values from high values to acceptable values. The same phenomenon happened around 50 minutes and 100 minutes after the warm-up period. Those reactions can be clearly seen in the Fig. 59.

In the third controlled area is clear that all of the controllers reacted most of the time. However, in the cell 13, there is a problematic point where the controllers caused the density increase. Such behavior is acceptable because, as it was mentioned, the controllers are not perfect and, sometimes, when causing improvements in some places it can cause the reverse effect in others places. This problematic point can be found in Fig. 60.

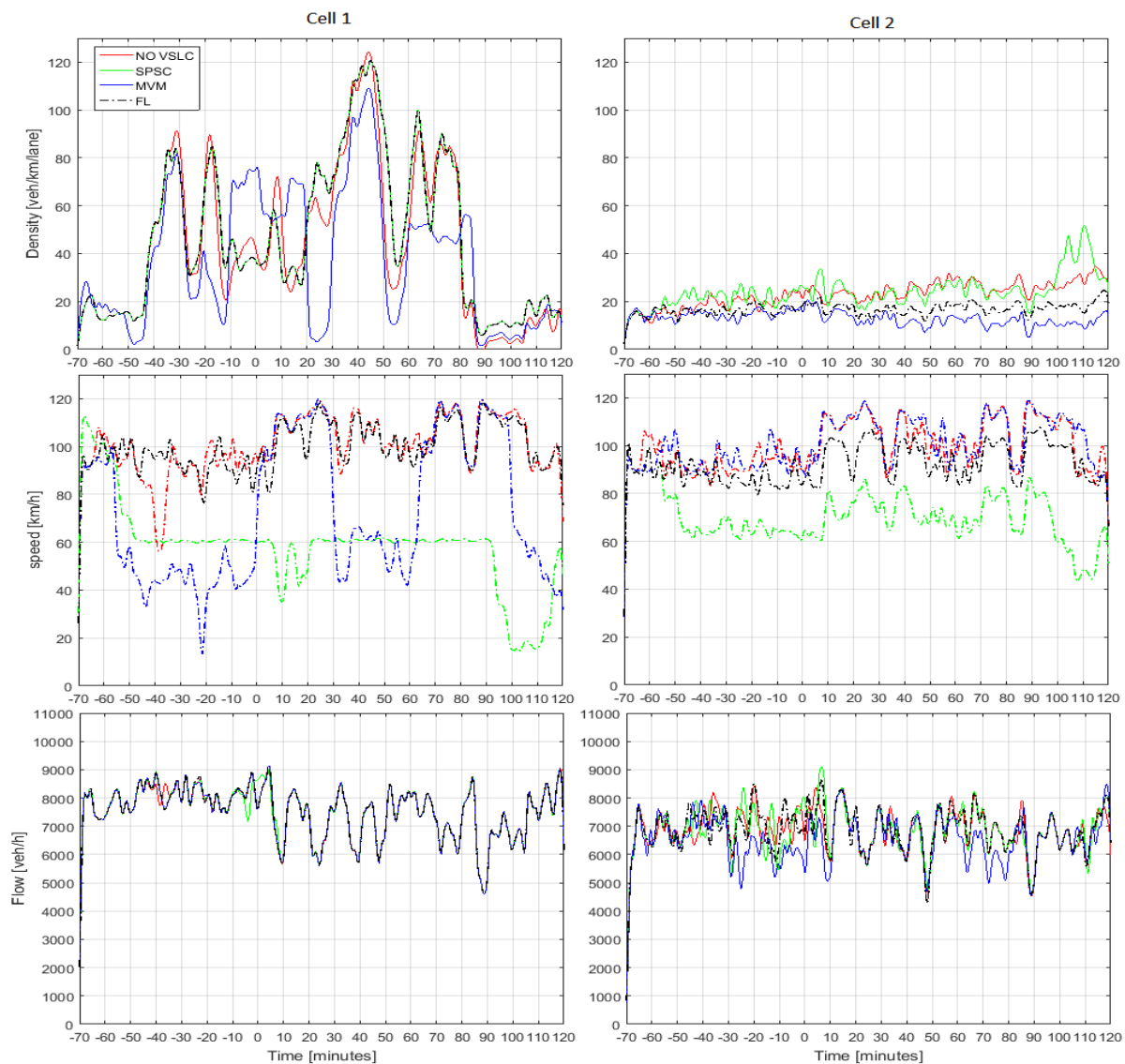


Figure 56 - Obtained density, average speed and traffic flow for the first controlled area.

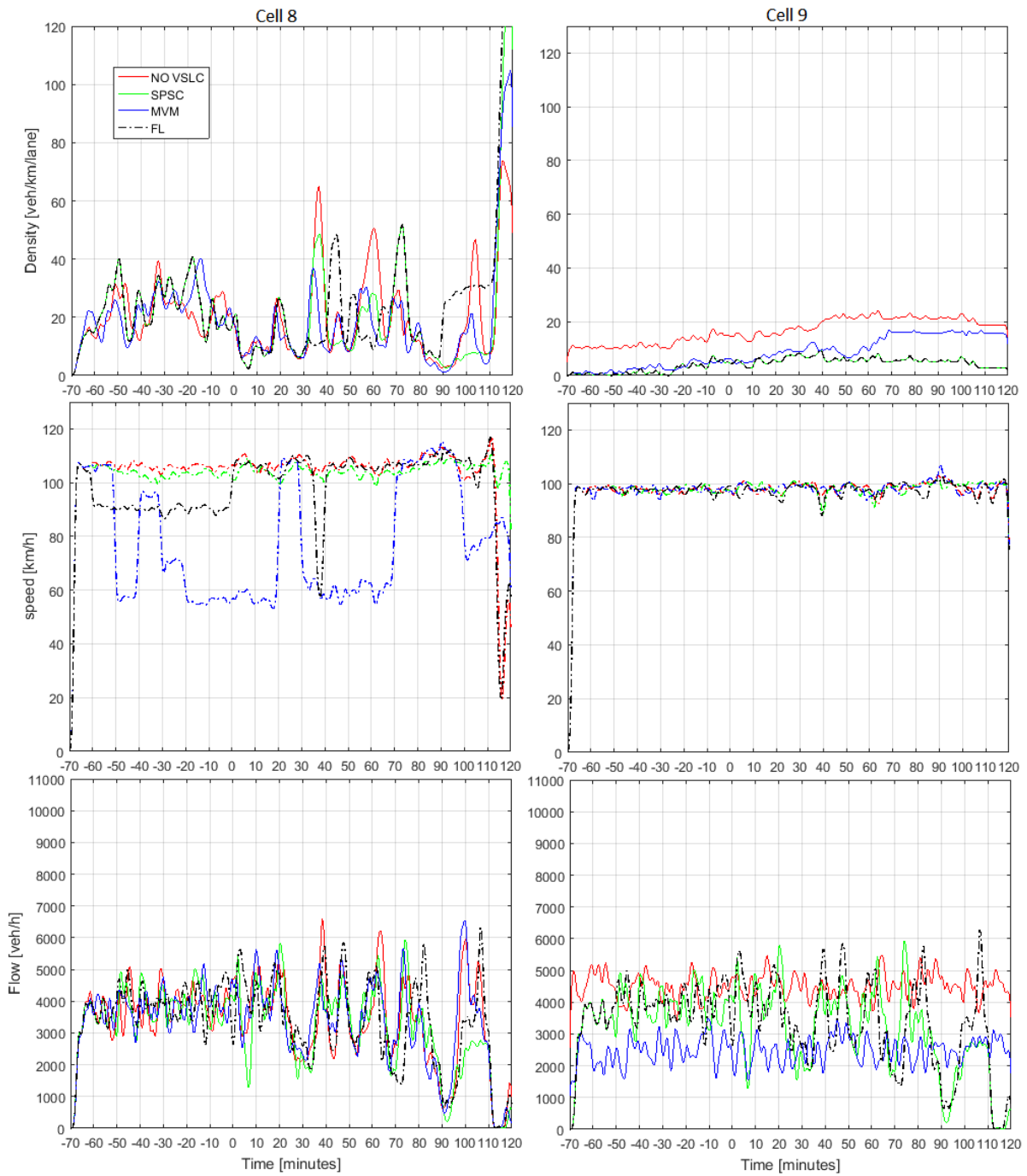


Figure 57 - Obtained density, average speed and traffic flow for the second controlled area.

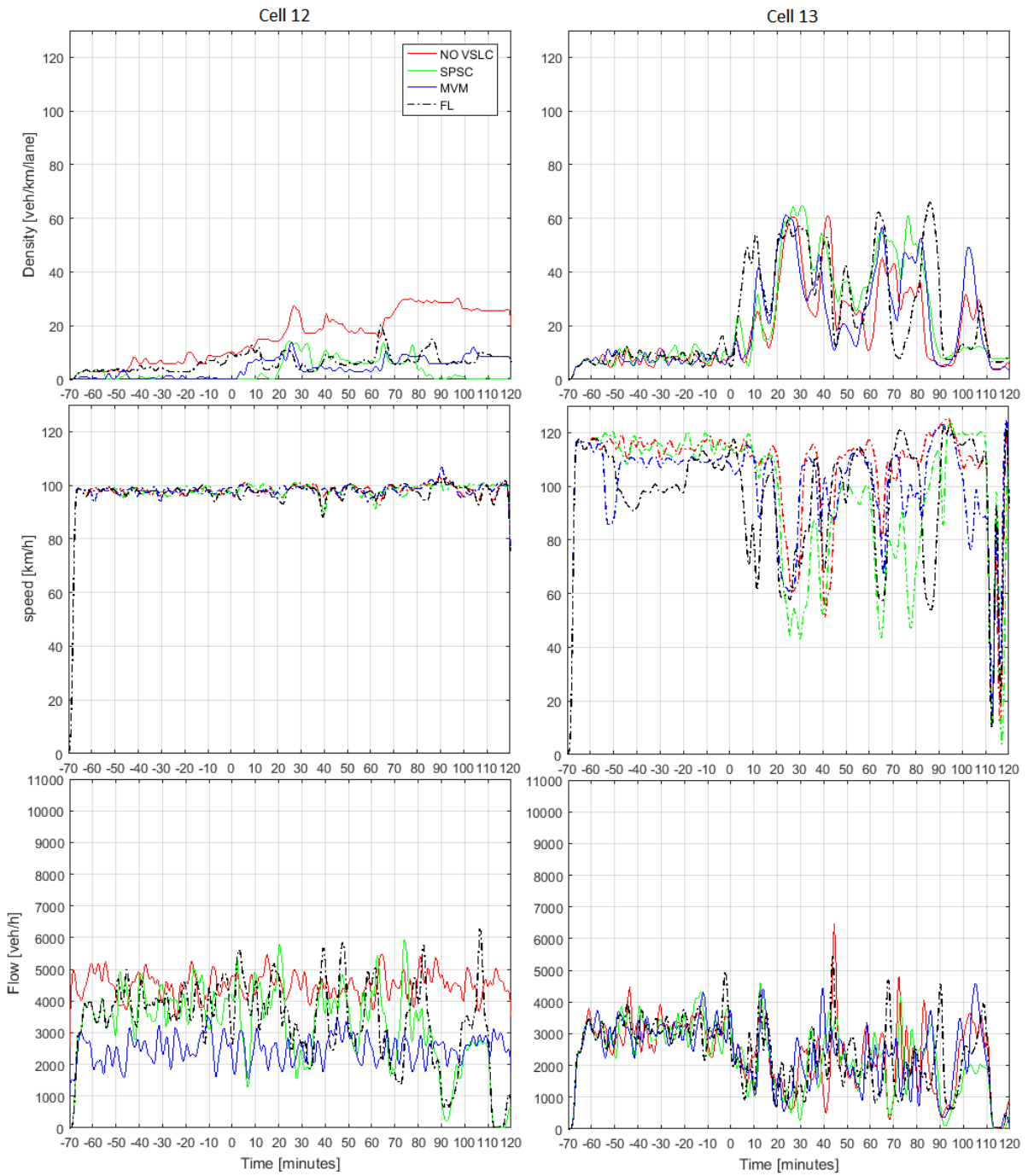


Figure 58 - Obtained density, average speed and traffic flow for the third controlled area.

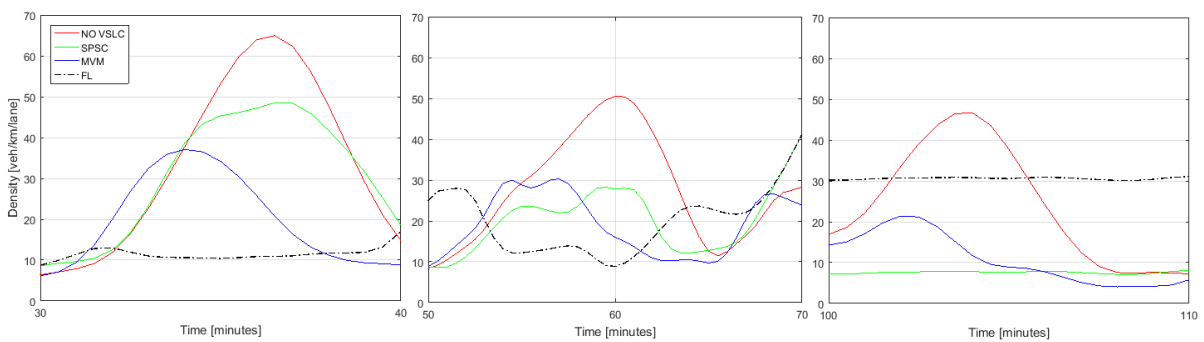


Figure 59 - Controller reaction on the second controlled area.



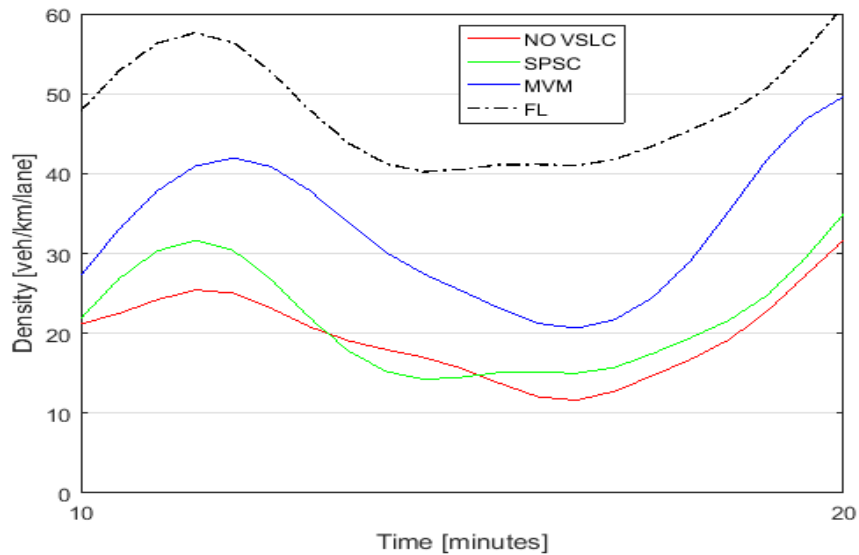


Figure 60 - Problematic point in the third controlled area (cell 13).

After doing the graph analysis, it is important to show the speed limit decisions. In Fig. 61, it is possible to notice that, because of the congested period, the speed limit has changed constantly. Besides that, because of the same problem, the speed limit got the lowest value many times. Due to the significant reduction of the speed limit, the queue lengths on the present on-ramp can get longer. Talking about the results, such phenomenon can be noticed in the queue length on the first on-ramp around the 60 minutes after the warm-up period (see Fig. 62). However, the controllers also got to reduce the queue lengths before happening it. The Fig. 63 shows the moment when the queue length got shorter by the implementation of the controllers.

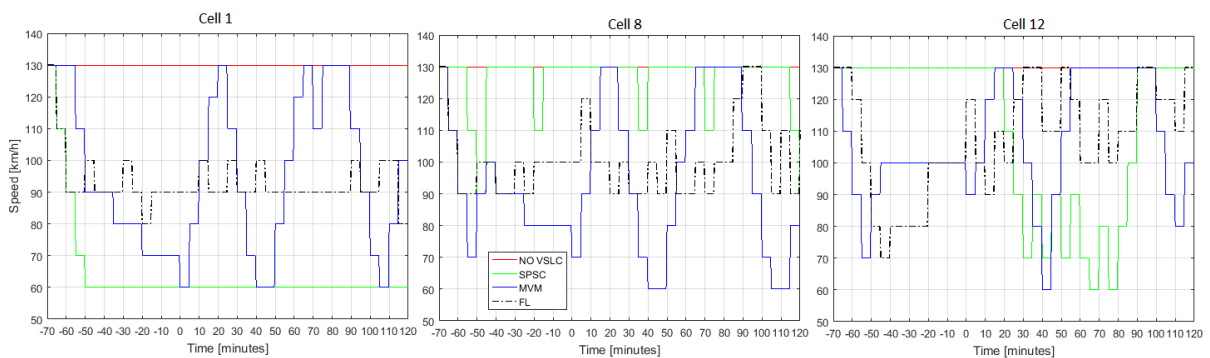


Figure 61 - Speed limit changes during the simulation.

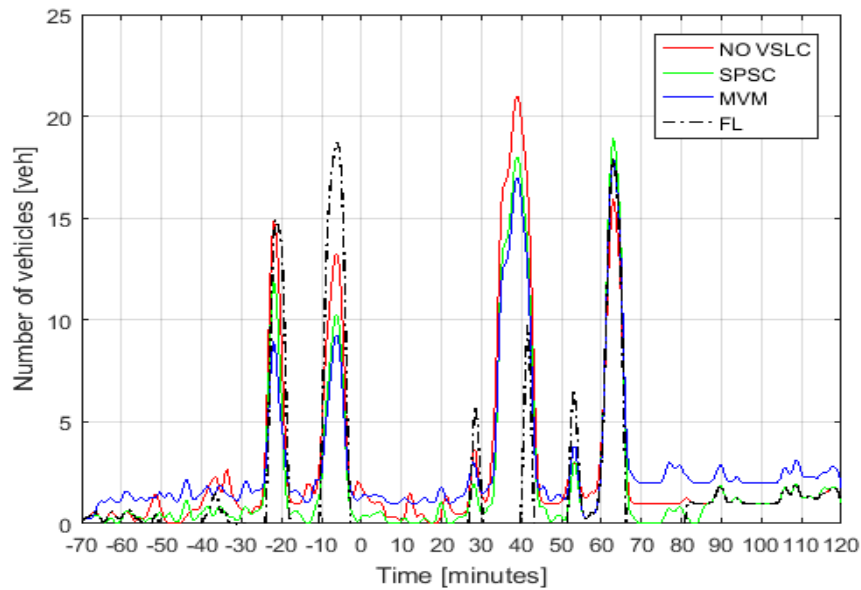


Figure 62 - Queue length on the first on-ramp.

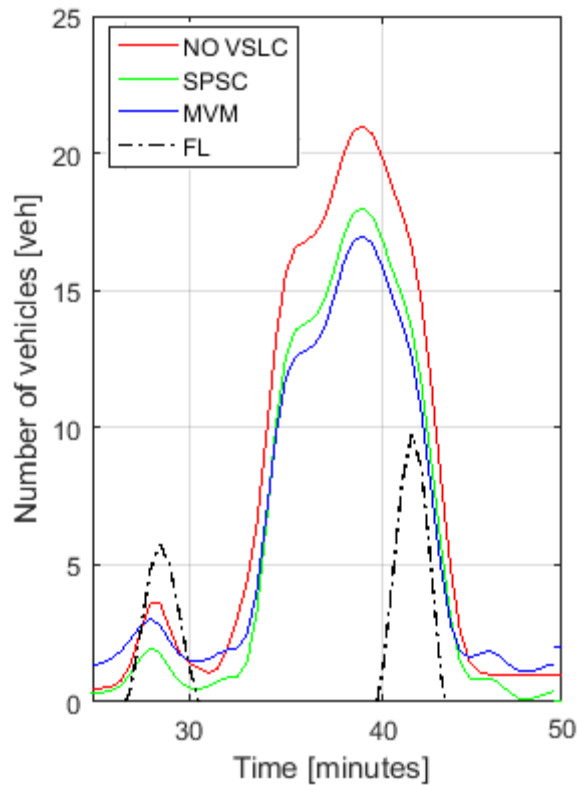


Figure 63 - Moment when the controllers caused the queue length reduction.

Since the graph analysis is not so clear for a period full of congestions, a quantitative analysis was done considering traffic parameters, besides showing the emission results (see Tabs. 22-23). It is good to mention that the used EnViVeR configuration for the emission results is the same as that used for the previous cases.

Despite the problem with the congestions in this period, the controllers got to reduce all of the comparison parameters in this case. Of course, the improvements were not significant, but, at least, the controllers could react. The fact of the improvements are not significant proves again that the controllers, when applied to a congested period, have the action limited.

**Table 22 - Quantitative analysis for the longer segment regarding the noon period.**

	No VSLC	SPSC		MVM		FL	
		Obtained	Red. [%]	Obtained	Red. [%]	Obtained	Red. [%]
<b>TTS [veh·h]</b>	11439	11372.51	0.6	10986.6	4	10996.1	3.87
<b>Average TT [s]</b>	622.6	621.7	0.1	617.3	0.9	598.45	3.88
<b>Maximal TT [s]</b>	1563.3	1534.9	1.8	1489	4.8	1889.7	-20.9
<b>Average delay [s]</b>	502.9	504.3	-0.3	474	5.7	489.31	2.7
<b>Maximum delay [s]</b>	1512	1503.6	0.6	1489	1.5	1356	11
<b>Average queue length [veh]</b>	2.3	2.3	0	2.1	10.9	1.25	45.7
<b>Maximal queue length [veh]</b>	20	23	-15	23	-15	20	0

Table 23 - Quantitative analysis for the longer segment regarding the noon period.

Emission type	No VSLC	SPSC		MVM		FL	
		Obtained	Red. [%]	Obtained	Red. [%]	Obtained	Red. [%]
CO <sub>2</sub>	16.43 · 10 <sup>6</sup> g	16.23 · 10 <sup>6</sup> g	1.2	15.92 · 10 <sup>6</sup> g	3.1	16.18 · 10 <sup>6</sup> g	1.52
	8.604 · 10 <sup>6</sup> g/h	8.498 · 10 <sup>6</sup> g/h	1.23	8.33 · 10 <sup>6</sup> g/h	3.15	8.475 · 10 <sup>6</sup> g/h	1.5
	232.3 g/km	229.18 g/km	1.3	225.17 g/km	3.07	228.4 g/km	1.7
NO <sub>x</sub>	40.40 · 10 <sup>3</sup> g	38.582 · 10 <sup>3</sup> g	0.5	38.74 · 10 <sup>3</sup> g	4.1	40.04 · 10 <sup>3</sup> g	-0.9
	21.20 · 10 <sup>3</sup> g/h	21.07 · 10 <sup>3</sup> g/h	0.6	20.33 · 10 <sup>3</sup> g/h	4.1	20.97 · 10 <sup>3</sup> g/h	-1.1
	0.5714 g/km	0.5680 g/km	0.6	0.5480 g/km	4.1	0.5651 g/km	-1.1
PM <sub>10</sub>	3078 g	3013 g	2.1	3019 g	1.9	3065 g	0.4
	1614 g/h	1580 g/h	2.1	1582 g/h	2	1605 g/h	0.56
	0.04353 g/km	0.0426 g/km	2.04	0.04271 g/km	1.87	0.04327 g/km	0.59

## **7. Conclusion**

Despite that highways are built for higher LoS, traffic congestion can occur (specially on urban highways, which is the present case) and consequently reduce the LoS on a particular stretch of the highway. Higher LoS can be achieved by affecting the fundamental diagram of the observed highway section. One of the used control approaches for affecting the mentioned fundamental diagram is VSLC. By reducing the mean speed on the highway mainstream lanes, VSLC enables speed homogenization and consequently reduces traffic congestions and air pollution, and induces a smaller possibility of traffic accidents.

In this technical report a comparison of three controllers for VSLC is given. Simple reactive speed limit controllers MVM and SPSC, and a controller based on fuzzy logic are compared in a scenario with and without VSLC. Comparative analysis is conducted on two highways stretches. The first highway stretch contains two on-ramps and two off-ramps and the second stretch contains four on-ramps and five off-ramps. Those stretches are analyzed for two different periods (non-congested morning period and congested noon period). The results showed that is not simple to conclude which controller is the best for getting better LoS, but it is possible to map which controller is the best for a considered traffic situation. That means the controllers have different reactions according to the imposed conditions and this technical report has given an overview how is the behavior of each controller in the observed cases. As a result different control laws for different traffic situations can be applied defining the need of a switching mechanism between different control laws.

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