EXPLORATORY STUDIES ON NETWORK OPERATION OF FUZZY SIGNAL CONTROLLERS

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ABSTRACT

Urban road systems usually present characteristics that require traffic control along their major roads, usually referred to as arterial network control. Fuzzy signal controllers (FSC) have proven to be effective in traffic control at isolated intersections, according to previous studies. Therefore, the evaluation on the suitability of using FSC at intersections belonging to arterial network is relevant so as to improve traffic operation on this road type. This paper presents exploratory studies aiming to evaluate the use of FSC, originally designed for isolated operations on intersections located in arterial networks. Aspects such as controllers' adaptive capability and suitability for network operation and impact of intersections' spacing on controller responses are analyzed. The results show the adaptive capability of the FSC considered for arterial network control, as well as promote cooperation among these controllers – this is a promising strategy. The impact of intersections' spacing on controller response and traffic performance is also demonstrated.

Keywords: fuzzy signal controller, network control, network operation

1- INTRODUCTION

Starting with the pioneering work of Pappis and Mamdani (1977), different woks have explored the use of fuzzy logic for signal control purposes. Most of them deal with traffic control at isolated signalized intersections.

Advantages of using fuzzy signal controllers (FSC) for traffic control at isolated signalized intersections, as compared to commonly used fixed time and actuated signal controllers, have been proven by different simulation and field studies (Niittymäki, 2001; Niittymäki and Nevala, 2001; Jacques et al., 2002a). Motivated by these findings, several studies geared towards the fuzzy signal controllers' components have been developed in the last few years. Among the components studied are: defuzzification methods (Jacques et al., 2002b); fuzzy reasoning methods (Jacques et al., 2002c); fuzzy set definitions for controller input variables (Jacques et al., 2005; Vaz et al., 2005); fuzzy controller general type (Andrade and Jacques, 2008a); and fuzzy rule base structure (Andrade and Jacques, 2008b). Although these studies have been based on FSC for isolated intersections, their results are valid for general applications in traffic control. Therefore, they provide important support for future developments in this type of controller.

A common conclusion in studies with FSC components is that the implementation of these components must take into account the characteristics of the intersection and traffic to be controlled.

Traffic control requirements in urban areas usually involve traffic operations in arterial networks. This situation demands investigations related to the use of FSC for arterial network traffic control. Although studies considering this subject can be found in literature, their fuzzy control structures are quite different from that used by FSC designed for isolated intersection traffic control. Among the reviewed works, only the one developed by Niittymäki (1999) makes analyses of the network control according to FSC designed for isolated operations. The results of this work, considered along with those from the studies with FSC components, show the importance of extending research on the subject. That is, to investigate the performance of FSC originally designed to control isolated intersections when used to control intersections into a network structure. In the following text, this type of FSC is referred to as isolated FSC.

In light of this, the present work makes a comprehensive analysis of the isolated FSC operation in arterial networks. It aims at: (i) verifying the adaptive capability of this type of signal controllers for network operations, global analysis and according to road type; (ii) evaluating the impact of network characteristics (in terms of the spacing among its intersections) on the control provided; and (iii) identifying the presence of traffic progression along the arterial road.

This paper is organized into five sections. Its first section describes the context of the subject addressed, along with the motivation and objective for the research developed. Section 2 presents a brief literature review on isolated fuzzy signal controllers' operations under network conditions. The methodology adopted in the development of this research is presented in Section 3. It includes information on the traffic simulation program used, cases studied, performance measures adopted, and general aspects of the analyses conducted. This study's results and respective analyses are presented in Section 4, and they are referred to at three levels: global, road type, and intersection. The last section, Section 5, presents conclusions and recommendations for future work.

2 – ISOLATED FUZZY SIGNAL CONTROLLERS IN NETWORK OPERATION

The literature review on fuzzy signal controllers shows that studies on fuzzy logic application to traffic control at signalized intersection networks have been performed by different researchers (Nakatsuyama et al., 1983; Kim, 1994; Chiu and Chand, 1993; Lee and Kwang, 1999). However, the control schemes presented in these works are different from those generally used in fuzzy logic controllers designed for operation at isolated intersections (called herein isolated FSC). As referred to in Section 1, the study conducted by Niittymäki (1999) evaluates the network operations of the fuzzy controller used in the FUSICO Project, originally designed to control isolated signalized intersections (Niittymäki, 1998). The results show that although the isolated FSC has the capability to network operations, it requires additional elements to facilitate coordination among the controllers examined.

The study of Niittymäki (1999) considered a signalized two-intersection network according to three different values of spacing between the intersections, which are: 200m, 500m and 1000m. Analyses were conducted for five volume levels, expressed in vehicles per hour. They are, for the arterial and secondary streets, respectively: 400x200, 400x400, 800x200, 800x400, and 1200x400). The following four alternatives for signalized intersection control were considered: (1) fixed-time coordinated control for both intersections, (2) vehicle actuated control for both intersections (which was considered as the reference control type for the study), (3) isolated fuzzy control for both intersections, and (4) vehicle actuated control for the first intersection and fuzzy control for the second one. Average delay, average queue lengths, average green time and performance index for each intersection approach, road type and total network are considered for the analyses. Signal timings for fixed-time control were calculated according to the Webster method.

The study's results indicate that the FUSICO controller version considered is adaptive to the traffic conditions evaluated, but it is not suitable to deal with congested situations. Also, in recognizing that the controller should provide coordination between signal timings of adjacent intersections, the author suggests two approaches for promoting this coordination: (i) providing suitable green split to favor the arterial traffic; (ii) creating a set or fuzzy rules to address the offset definition between the network intersections. Another relevant aspect addressed was the road length between the intersections. The study shows that distances of 200 and 500 meters cause the need for signal coordination, while for the distance of 1000 meters its results were not conclusive. The results show that higher benefits for coordination were found for situations with closer intersections.

The author's second suggestion seeks to create fuzzy rules where the controller output variable might represent the time for the beginning of the green time for a signal group, in order to favor arterial traffic movements, that is, represent offset values. Nakatsuyama et al. (1983) present a similar approach and named the controller rule base related to the offset as "Fuzzy Phase Controller (FPC)". The work of Chiu and Chand (1993) also brings a rule base developed to adjust the network offsets.

The results found by Niittymäki (1999) show the importance of a study on the consequences of using isolated FSC for network control purposes. However, the aforementioned study just considers a two-intersection network. This may impose limitations to the evaluation intended of traffic fluidity along an arterial road controlled by isolated FSC, as well as on the impact of intersections' spacing on the controller response and traffic performance. In light of this and given the original study as a reference, this present work aims to consider some alternatives of four-intersection network configurations, all controlled by isolated FSC. In addition, the FSC to be studied has a substantial difference on the rule-base structure in comparison to the FUSICO controller described by Niittymäki (1999). In the present case, the controller has just one set of rules, applied for all extensions to be delivered by the fuzzy controller. It is basically the controller used in previous studies on FSC developed by Jacques et al. (2002b, 2002c and 2005) and described in Jacques et al. (2005).

3 - METHODOLOGY

Following the literature review, this research was conducted based upon the following steps: choice of traffic micro simulation program to be used for evaluating traffic controlled performance under the control alternatives studied; complete description of the scenarios to be evaluated with the traffic simulator; definition of traffic and control performance measures to be used in the analyses conducted; and definition of the analysis methods for the results of the performance measures given by simulation for each situation considered. Each of these steps is presented in this section.

3.1 Traffic Simulator

The traffic simulator selected for this work is the UnB-Sitracs program. It is a microscopic traffic simulator developed for academic purposes, which is able to represent three traffic control modes for signalized intersections (fixed-time, semi-actuated, and fuzzy). It allows for the representation of both isolated and in arterial network intersections. This software was developed at the University of Brasília, by members of its research group involved at ongoing fuzzy signal controller studies. The simulator executable file and the program User Manual are available for free downloading on the Internet at the following address: http://sourceforge.net/projects/unb-sitracs/files/.

The main models of UnB-Sitracs are related to three simulation aspects:

(a) *Traffic flow generation:* the vehicles to be simulated are generated according to their time headways. These headways are randomly calculated based on a right shifted negative exponential function, whose parameters are the minimum headway and the average headway (calculated from traffic volume).

(b) *Vehicle behavior in the microscopic approach:* the car following model of Gipps (1981) is used to represent the vehicles' movements along a given road segment and intersection. This model adjusts each vehicle speed as a function of its desired speed, acceleration and deceleration rates, among other parameters, considering all the elements that interact with the vehicle along its way (other vehicles or traffic signals, for instance).

(c) *Lane changing procedure:* the program considers the decision-making framework for lane changing proposed by Gipps (1986). The main elements of this decision framework, implemented into the UnB-Sitracs, are: (i) lane selection; (ii) possibility for lane changing; (iii) driver behavior according to the vehicle proximity to a desired turn movement; (iv) urgency for lane changing; (v) driver behavior at a medium distance from a desired turn movement; (vi) comparative advantages between current and target lanes; (vii) impact of heavy vehicles; (viii) impact of vehicle ahead; (ix) safety factor; (x) changing target lane.

The performance measures calculated by UnB-Sitracs, which are presented at the program basic report, are: average number of stops per vehicle; percentage of stops; average delay per vehicle; average green time for signal phases; and average speed.

Details on the UnB-Sitracs models and the performance measures calculated by the program, as well as guidelines for its use, are presented in the User Manual (UnB-Sitracs, 2009).

3.2 Situations to be analyzed

To simulate road traffic situations using UnB-Sitracs, all geometric elements of the intersections and road segments located between them must be defined. In addition, the traffic operation characteristics and signal controller type and respective parameters at each intersection have to be well specified. In the following text, the information related to the situations under analysis is presented.

(a) *Traffic operation*: traffic operation characteristics include operating speed, traffic flow and composition, and other characteristics of each vehicle type to be simulated. The values adopted in this work are presented in Table 1.

(b) *Geometric elements of the network*: the arterial road studied is a four-intersection open network. The distances between adjacent intersections are equal to “A” and “B” meters, as shown in Figure 1. The horizontal road is considered an arterial road, and the vertical crossing roads are classified as secondary. All of them are two-lane one-way roads, with each lane having width equal to 3.5m. There are no horizontal curves and the grade of all roads is null. Stop lines are located 1(one) meter upstream of the intersections to all approaches. No turning movements are permitted but lane changing is possible. The spacing between the intersections is considered on two different ways: (i) equal to each other, that is “A” = “B”; (ii) the first and the last spacing (between intersections 1 and 2, and between intersections 3 and 4) are equal to “A”, different from the spacing between intersections 2 and 3 that is equal to “B”. The selected values to be considered in the present work were defined based on the literature referred values for spacing among signalized intersections that effectively requires coordinated control. The following four network configurations were defined to be addressed during the exploratory studies: *(1)* network 111 (100*m*-100*m*-100*m*), *(2)* network 333 (300*m*-300*m*-300*m*), *(3)* network 313 (300*m*-100*m*-300*m*) and *(4)* network 131 (150*m*-350*m*-150*m*).

Table 1 Elements related to traffic operation

Elements	Description
Operating speed	Considering urban network, the following speed distribution was adopted: 2% at 30km/h, 15% at 40km/h, 70% at 50km/h, 10% at 60km/h and 3% at 70km/h.
Traffic volume	The traffic volumes to be simulated represent three operation levels, defined according to the degree of saturation calculated for all approaches (considering fixed-time control [(2)]). The secondary road volume is approximately 30% of the arterial volume. The volume levels studied are: High Volume: 2200 x 660 vph[(1)] (Degree of saturation: 0.89 x 0.87) Medium Volume: 1600 x 500 vph[(1)] (Degree of saturation: 0.72 x 0.72) Low Volume: 1200 x 400 vph[(1)] (Degree of saturation: 0.50 x 0.50)
Traffic composition and vehicle operating characteristics [(3)]	In order to reduce the factors affecting the general traffic behavior, it was assumed that all vehicles are passenger cars.

(1) Vehicles per hour.
(2) See Table 2.
(3) Detailed data available in Andrade, 2009.

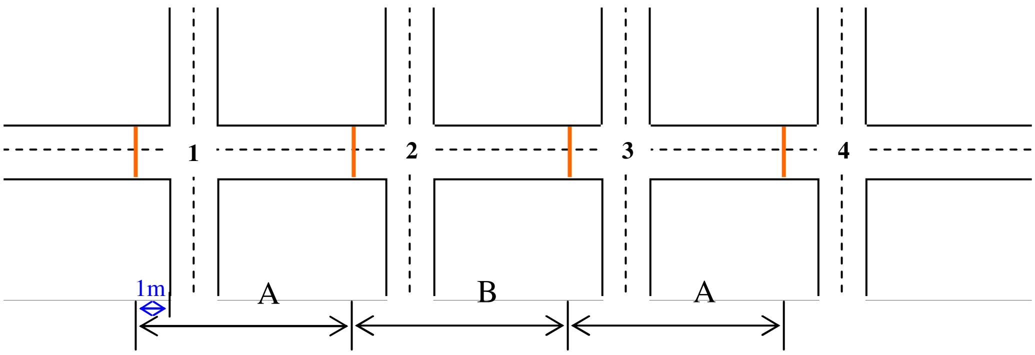


Figure 1 Schematic representation of the road segment studied

(c) *Signal controllers*: the present study considers two types of signal controllers, which are: fixed-time controller, operating in coordinated mode, and fuzzy controller. Fixed-time controller requires the signal timing calculations for each volume level, including offset values for each network configuration defined. The cycle length and split calculations for the fixed-time (pretimed) control were done using the Webster and the Critical Degree of Saturation methods. These calculations considered isolated operation and are presented in Table 2. The offsets were defined based on time-space diagrams drawn for each network configuration studied.

Table 2 Signal timings for each traffic volume level

Volume Level	Average Volume		*IG*	*Y*	*AR*	*T*	Cycle	Effective green		*X*	
	Princ.	Sec.						Princ.	Sec.	Princ.	Sec.
High	2200	660	5	4	1	10	95	65	20	0.89	0.87
Medium	1600	500	5	4	1	10	52	32	10	0.72	0.72
Low	1200	400	5	4	1	10	50	30	10	0.50	0.50

where,

- average volume is given in vehicles per hour;
- Intergreen (*IG*), Yellow (*Y*), All Red (*AR*), Total lost time (*T*);
- Cycle and Effective Green are given in seconds;
- Degree of saturation (*X*)

Details on the elements of the fuzzy signal controller used in the present study can be found in Andrade (2009). In terms of its general operating conditions, the following applies:

- minimum green time equal to 5 seconds for all approaches;
- maximum number of sequential green extensions for each phase is equal to 5;
- if one extension calculated is less than or equal to 2 seconds, after its end no other extension can be given;
- a traffic detector is placed at each lane, at 100 meters upstream the stop line.

3.3 Performance Measures

Among the performance measures calculated by UnB-Sitracs, the following were selected for the analyses proposed: average delay per vehicle, percentage of stops, average number of stops per vehicle, and the average green time. The average delay calculated by the program corresponds to the average control delay. That is, it considers the difference between the effective time the vehicle takes to move along the road segment studied and the time it would take if the same movement was made at the vehicle desirable speed.

The need for future statistical analysis of the simulation results caused each situation to be analyzed was simulated during 30 independent hours. The simulation results regarding each situation considered, expressed by means of the performance measures, are given in global average values and in average values per intersection, for each simulation hour.

3.4 Methods of Analysis

The analyses were performed according to two different approaches: descriptive analysis, based on graphics for the overall 30 simulation hours, and application of statistical tests for verifying the statistical significance of differences among simulation results produced for distinct situations studied.

The tests of significance initially defined for the study were the Analysis of Variance (ANOVA) and the Test of Tukey. Applications of these tests require the normality of the groups (samples) and the homogeneity of the variances of the groups compared. Should these hypotheses be not met, the following non-parametric tests were applied: Wilcoxon, for two-group analyses; and Kruskal-Wallis for analyses of two or more groups.

The verification of the normality of each group of data was made by the application of four tests. They are: Shapiro-Wilk, Kolmogorov-Smirnov, Cramer-von Mises and Anderson-Darling. For the present studies, a group is considered not "normal" if two or more tests indicate that the difference between its probability distribution and the normal distribution is statistically significant. In the presence of not normal groups, the simulation results are compared by non-parametric tests. If the groups are normal, the verification of the homogeneity of their variances is then performed by means of the test of Levene. In the homogeneity case, the tests with the simulation results are parametrics (ANOVA and Tukey); in the opposite case, non-parametric tests are applied (Wilcoxon and Kruskal-Wallis). All statistical tests were applied with the use of software SAS® (Statistical Analysis System), with the support of the University of Brasilia's Department of Statistics.

The analyses of the simulation results consider three main levels:

- *Global analysis:* evaluation of the impacts caused by network configurations on controller operation, and comparison between the global network performance measures provided by the two signal control modes tested;
- *Analysis per road type:* evaluation of traffic progression characteristics along the arterial road and its impacts on secondary roads;
- *Analysis per intersection:* evaluation of network operation effects at intersection approaches level.

4 – RESULTS AND ANALYSES

This section contains the results provided by simulation of the situations tested, along with the respective analyses (global, per road type, and per intersection). A summary of the different network and traffic characteristics studied is presented in Table 3. This table also shows the notation used to represent the characteristics studied, aiming to simplify the presentation of the simulation results in tables and graphics.

Table 3 Summary of characteristics studied

Control Mode		Volume Level[1]		Network	
Fix-Coor	Fixed-time coordinated	HV	High = 2200 x 660	111	100m-100m-100m
Fuz	*Fuzzy*	MV	Medium = 1600 x 500	333	300m-300m-300m
-	-	LV	Low = 1200 x 400	131	150m-300m-150m
-	-		-	313	300m-100m-300m

[1] *Volumes in vph*

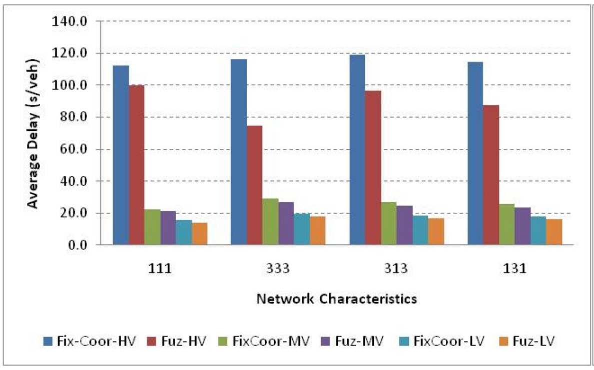
4.1 Global Analysis

This analysis aims to evaluate the impact of control modes and network configurations on overall network traffic performance.

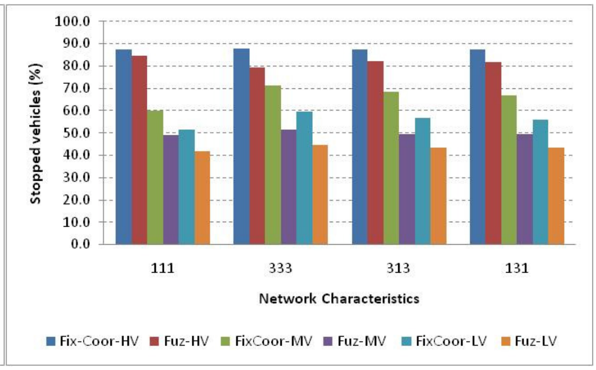
4.1.1 Analysis 1: Control mode

The traffic in arterial road performance evaluation is done by comparing the performance measures provided by simulation to traffic operation under the control modes considered: fixed-time coordinated and fuzzy.

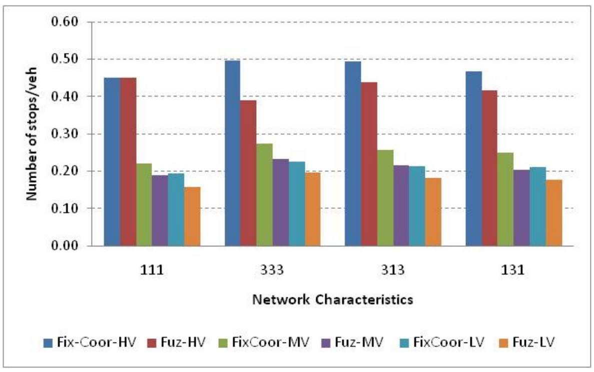
Figure 3 shows the graphic representation of the average values of the performance measures calculate by the simulator to all networks studied. In every case the fuzzy controller related results are better than those provided by the fixed-time coordinated control. Although performance pattern across the different networks and volume levels are similar for both control modes, the respective global average values of the performance measures are significantly smaller for the fuzzy control mode (except for the number of stops per vehicle at network 111 in high volume situation). The excessively high average delay values, observed for high volume levels in all situations, are caused by the low average speed of vehicles travelling along the arterial road under this heavy traffic condition.



(a) Average delay



(b) Stopped vehicles (%)



(c) Number of stops per vehicle

Figure 3 Network average values of the performance measures considered (Analysis 1)

Considering the high volume condition, it is observed that the average delay is the performance measure with the greatest difference between the two control modes (Figure

3a), reaching values around 36%. The differences on average delay for medium and low volumes are in the range of 4% to 11%. All referred to differences are statistically significant for α=5% (see AD_NW column in Table 4).

For the percentage of stopped vehicles (Figure 3b), the results show better performance for fuzzy control, with differences between the two control modes around 28% for the medium and low volumes. The biggest difference in percentage for the high volume is about 9.6%, which is quite similar across all network configurations examined. The *p*-values for these differences are presented in %Stops_NW column in Table 4. They show that all differences are statistically significant.

The results for the number of stops per vehicle, presented in Figure 3c, show that the differences observed are similar across all four network configurations, when considering the medium and low volumes. For the high volume, the differences vary across the networks. In network 111 it is quite small (0.1%) and is not statistically significant (see Stops/veh_NW column in Table 4).

Table 4 *p*-Values for ANOVA and Wilcoxon tests regarding the control mode analysis

Network/Volume		AD_NW	%Stops_NW	Stops/Veh_NW
111	High	<.0001	<.0001 *	0.9622
	Medium	0.0191 *	<.0001	<.0001 *
	Low	<.0001 *	<.0001	<.0001 *
333	High	<.0001 *	<.0001 *	<.0001 *
	Medium	<.0001 *	<.0001	<.0001 *
	Low	<.0001	<.0001	<.0001 *
313	High	<.0001 *	<.0001 *	<.0001
	Medium	<.0001 *	<.0001	<.0001 *
	Low	<.0001	<.0001	<.0001 *
131	High	<.0001	<.0001 *	<.0001
	Medium	<.0001	<.0001	<.0001 *
	Low	<.0001	<.0001	<.0001 *

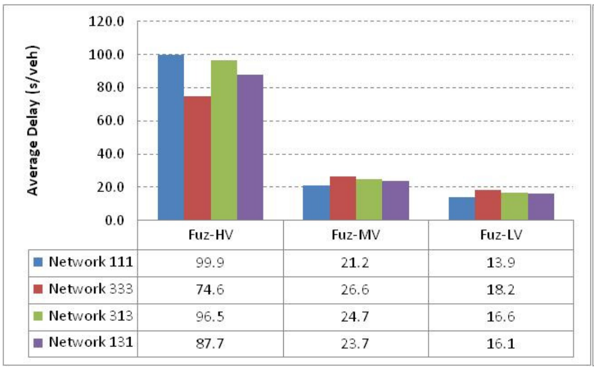
** p-values for Wilcoxon test.*
The difference is statistically significant for p ≤ 0,05.

In general terms, the fuzzy controller tested in this study, although not designed for network control, provided better global traffic performance than the fixed-time coordinated control analyzed. This latter was programmed according to the traffic volumes and network configurations studied. A relevant aspect to consider is that the benefits to traffic performance achieved by the fuzzy control are statistically significant for α=5%.

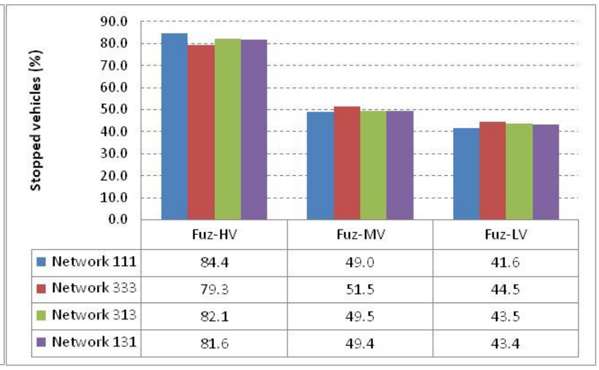
4.1.2 Analysis 2: Network configuration

The global analysis of the system performance under fuzzy control, as a function of the spacing among successive intersections (referred to as network configuration herein), is very important in the context of this study. It is a way of studying the behavior of platoons formed in one signalized intersection on their way to the downstream ones. The more platoons succeed in travelling without stops through the downstream intersections, the better the overall traffic performance. This type of traffic operation is strongly affected by the spacing among the successive intersections. This spacing is taken into account for the offset calculations in fixed-time coordinated control mode.

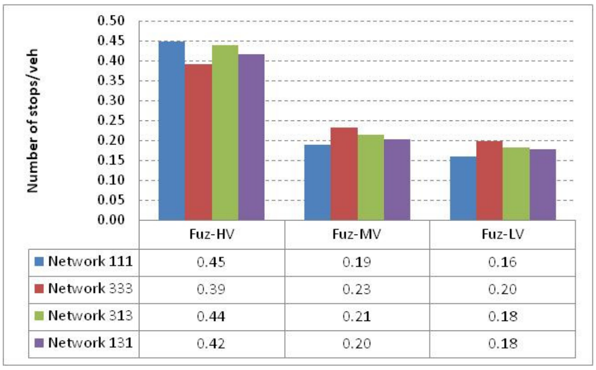
Figure 4 shows the average value of the performance measures produced by UnB-Sitracs for the network configurations studied. These measures are related to the overall network. The graphs show that for the medium and low volumes, the performance measures pattern is similar across to the different configurations. For these volumes, the three performance measures are smaller in network 111. In ascending order, they increase in networks 131, 313 and 333. For the high volume, in opposite way, the best results are related to network 333 and the worst to network 111.



(a) Average delay



(b) Stopped vehicles (%)



(c) Number of stops per vehicle

Figure 4 Network average values of the performance measures considered (Analysis 2)

The operation of the high volume tested in network 111 (spacing among intersections equal to 100m) causes vehicles queued at an intersection approach affect significantly the traffic fluidity at downstream road segments. For the medium and low volumes studied, the queue length is usually not big enough to cause the same impact. However, it is important to register that the results previously discussed referred not only to the arterial road. Therefore, a more detailed analysis per road type is required to understand the impact of the intersections distances on traffic behavior at arterial and secondary roads' approaches.

For each volume level and performance measures, the statistical significance tests revealed that the results are significantly different per network configurations. Table 5 shows the results of the statistical analysis, where AD_NW is the global network average delay,

%Stops_NW is the global network percentage of stops, and Stops/veh_NW is the global network number of stops per vehicle. A complementary statistical analysis was then performed in order to identify the pairs of networks that differ among each other. Tukey and Wilcoxon tests was used for this matter, following the criteria presented in Section 3.4

Table 5 *p*-Values for ANOVA and Kruskal-Wallis tests regarding the network configuration analysis

Volume	AD_NW	%Stops_NW	Stops/Veh_NW
High	<.0001 *	<.0001 *	<.0001 *
Medium	<.0001	<.0001	<.0001 *
Low	<.0001	<.0001	<.0001 *

* *p*-values for Kruskal-Wallis test.
The difference is statistically significant for p ≤ 0.05.

In general, the latter tests showed that spacing between successive intersections significantly affects the traffic operation from one network to another. The exceptions found to this general finding are:

a) High Volume
   a.1 – Average delay: 111 = 131
   a.2 – Percentage of stops: 313 = 131
   a.3 – Stops per vehicle: 313 = 111
b) Medium Volume
   b.1 – Percentage of stops: 313 = 131 = 111
c) Low Volume
   c.1 – Average delay: 313 = 131
   c.2 – Percentage of stops: 313 = 131

4.2 Analysis per road type

This analysis considers the traffic performance measures grouped by road type. It intends to investigate separately the impact of control mode and network configuration on traffic performance along the arterial road and secondary roads.

4.2.1 Analysis 1: Control mode

The simulation results show that the values of traffic performance measures for the whole bunch of secondary roads are smaller under fuzzy control than when the fixed-timed coordinated control is applied. As should be expected, this situation is opposite for the traffic at the arterial road, for which the fixed-time coordinated control is in general more effective. All these differences in performance are statistically significant for α=5%. The specific statistical tests results are available in Andrade (2009).

However, the benefits the fixed-time coordinated control provides for the arterial road traffic do not compensate the reduction in performance measures caused by fuzzy control to the secondary road traffic. For this reason, the global analysis presented in Section 4.4.4 indicates that the fuzzy control is more beneficial to the whole network traffic.

As an example, Figure 5 shows the average delay simulation results for the arterial and secondary roads. In addition, Table 6 presents the relative difference on this performance measure between the groups of roads considered (secondary road delays over arterial road delay). The results are related to the low volume and consider all road configurations studied.

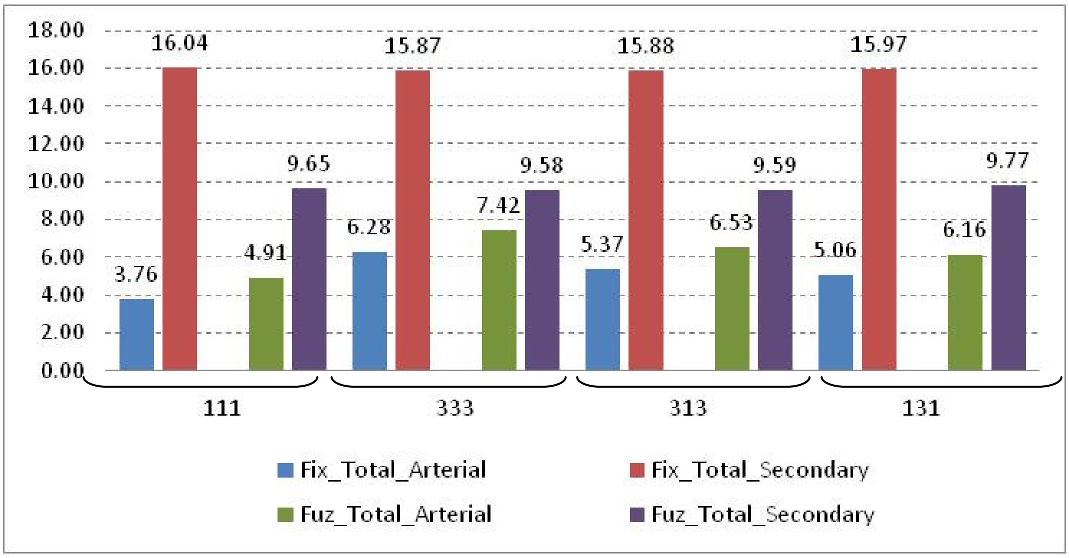


Figure 5 Average delay per road type – Low Volume

Table 6 Relative difference between average delay measures for secondary and arterial roads – Low Volume

Network	Fixed-time coordinated	*Fuzzy*
111	326.5%	96.8%
333	152.9%	29.2%
313	195.7%	47.0%
131	215.5%	58.6%

Table 6 makes clear the fuzzy control also benefits the arterial traffic but, in doing so, it causes less difficulty to the secondary road traffic than the fixed-time coordinated control does. For the other performance measures considered in the present work, the fuzzy control capability to reduce the difference between the results of the two groups of roads in the network operation was also verified.

Further, the performance lost for the arterial traffic under the fuzzy control mode, as compared to the fixed-time coordinated control, is not small. For the average delay at low volume level, for instance, it varies from 18.2% (network 333) to 30.6% (network 111). This suggests the need for a procedure that provides "cooperation" among the fuzzy controllers at the network level.

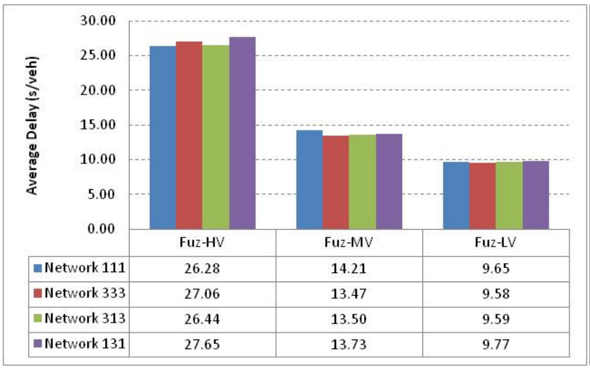
In considering the other performance measures (percentage of stops and number of stops per vehicle) for the high volume level, the simulation results indicate that for the arterial traffic the fuzzy control is more beneficial than the fixed-time coordinated control for the network 333 and more detrimental to the network 111. For the other volume levels, the simulation results do not indicate a network configuration that is more favorable to fuzzy control for the sake of these measures.

In relation to the response of fuzzy controller to the traffic volume studied, under the different network configurations, the simulation results show that the average green time provided by this controller to the arterial approaches is, on average, 35% less than the corresponding green time of the fixed-time controller. For the secondary road approaches this reduction is even higher, being on average equal to 45%.

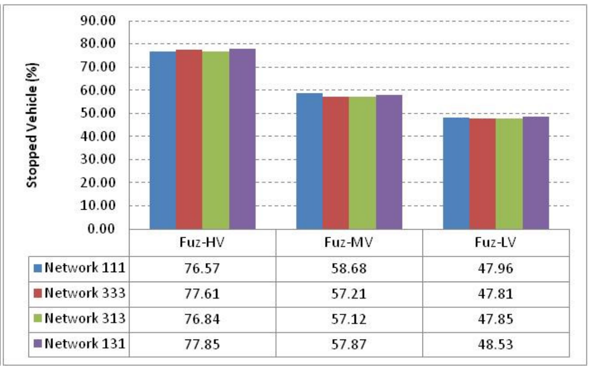
4.2.2 Analysis 2: Network configuration

The analysis related to network configuration aims to identify the impact of varying the distance among the network intersections on fuzzy controller response and traffic performance. The controller response is related to the average green time that was delivered to each signal phase. For the performance measures analysis the aggregated results for all approaches of each road type were considered.

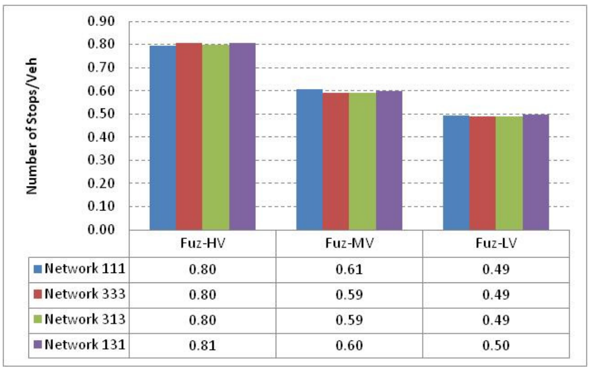
The results of simulations show that traffic performance measures are not so different for all networks studied when considering only the secondary roads (see Figure 6), while for the controller response the differences are more evident, as per Figure 7. For the arterial road, the results presented in Figures 8 and 9 show that the absolute differences in controller response and traffic performance are greater. The majority of these differences are statistically significant for α=5%.



(a) Average delay

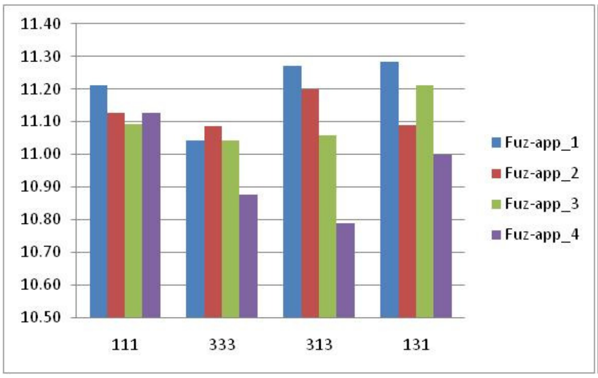


(b) Stopped vehicles (%)

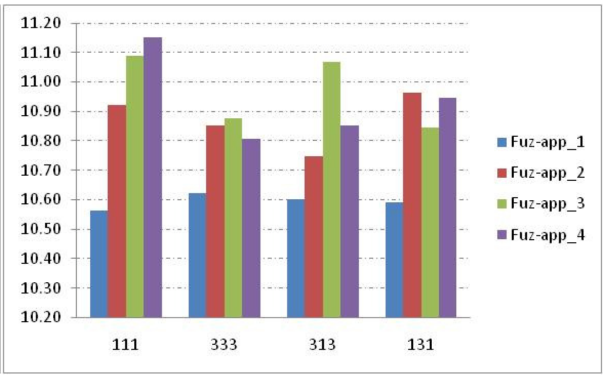


(c) Number of stops per vehicle

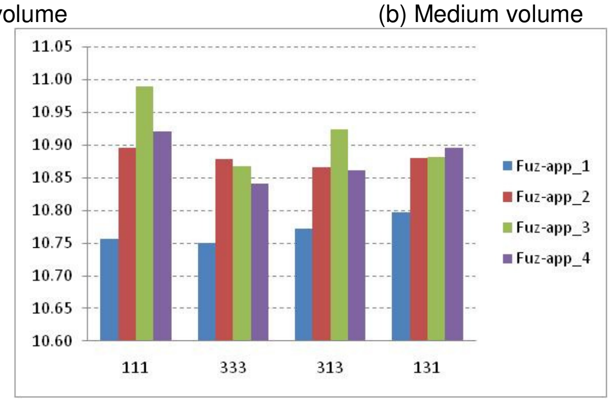
Figure 6 Secondary roads average values of the performance measures considered (Analysis 2)



(a) High volume

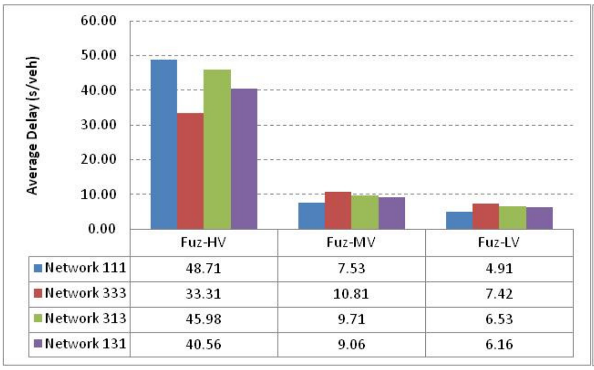


(b) Medium volume



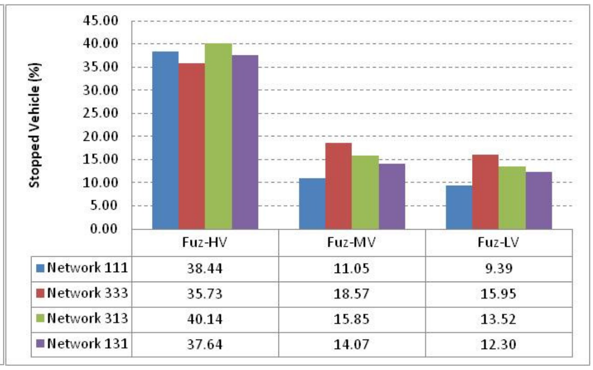
(c) Low volume

Figure 7 Average green time for the secondary road approach of each intersection



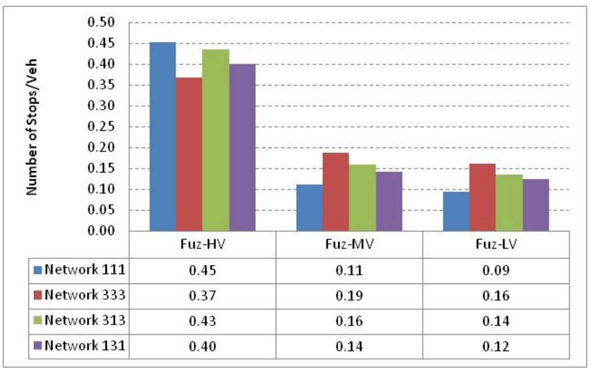
	Fuz-HV	Fuz-MV	Fuz-LV
Network 111	48.71	7.53	4.91
Network 333	33.31	10.81	7.42
Network 313	45.98	9.71	6.53
Network 131	40.56	9.06	6.16

(a) Average delay



	Fuz-HV	Fuz-MV	Fuz-LV
Network 111	38.44	11.05	9.39
Network 333	35.73	18.57	15.95
Network 313	40.14	15.85	13.52
Network 131	37.64	14.07	12.30

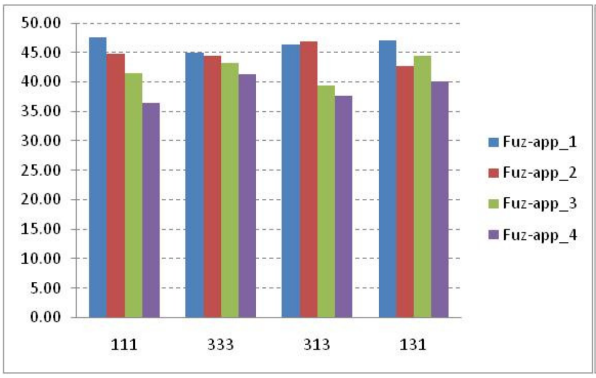
(b) Stopped vehicles (%)



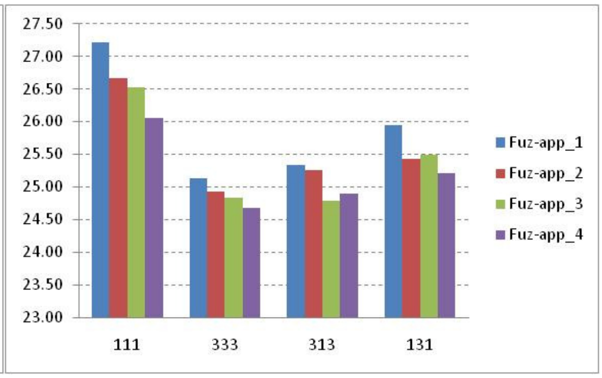
	Fuz-HV	Fuz-MV	Fuz-LV
Network 111	0.45	0.11	0.09
Network 333	0.37	0.19	0.16
Network 313	0.43	0.16	0.14
Network 131	0.40	0.14	0.12

(c) Number of stops per vehicle

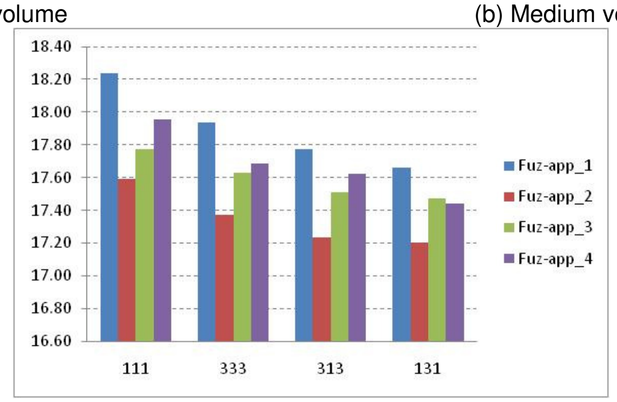
Figure 8 Arterial road average values of the performance measures considered (Analysis 2)



(a) High volume



(b) Medium volume



(c) Low volume

Figure 9 Average green time for the arterial road approach of each intersection

Therefore, the present analysis confirms that fuzzy control is sensitive to network configuration, especially in relation to traffic performance at the arterial road. Although the previous results show that this control is less effective than the fixed-time coordinated control for the arterial road traffic, it is able to provide some progression effect for this traffic. Again, the quality of this progression depends on the distance between successive intersections. This aspect is further explored in the next section.

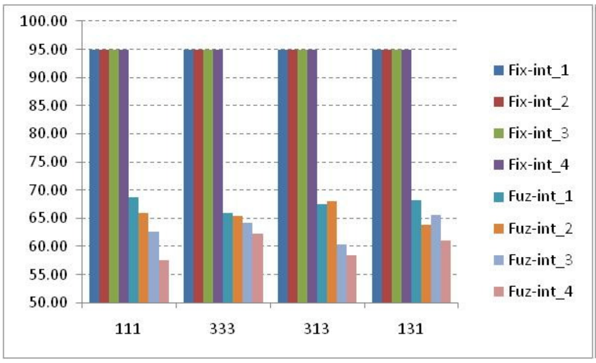
4.3 Analysis per intersection

The analysis per intersection has the following objectives: (i) to test if the differences on the control modes studied (fuzzy and fixed-time coordinated) are significant at intersection level; (ii) to verify the presence of traffic platoon progression along the intersections of the arterial road under fuzzy control.

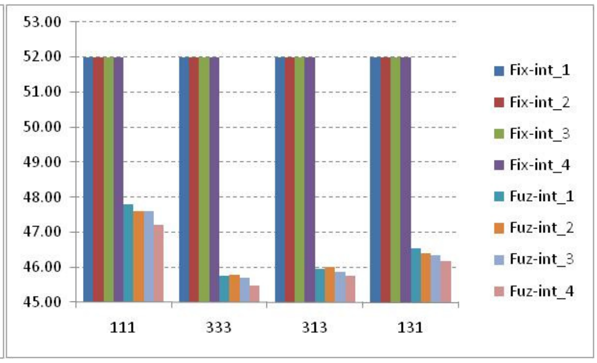
4.3.1 Controller response

The fuzzy controller response at each intersection is affected not only by the traffic volume to be controlled but also by the network configuration. For the fixed-time coordinated controller, the green time of the signal phases (and, therefore, the cycle time) is constant for all intersections, being calculated based on the hourly volumes studied (see Table 2).

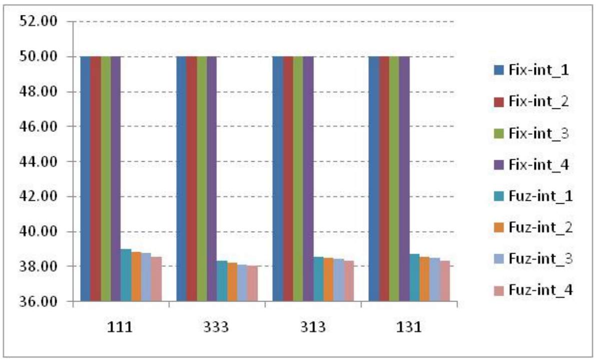
Figure 10 shows that the cycle times provided by fuzzy controllers are smaller than the corresponding values for fixed-time controllers. In all situations they are at least 10% smaller. On average, they differ up to 32.5%, as can be seen in Table 7. For each volume of this table, the value presented to fuzzy controller is the mean cycle length considering all network intersections and configurations. According to the characteristics of the fuzzy controller operation, the maximum possible value for its cycle length is 120 seconds. However, the maximum value provided by this controller type for the situations studied was 68.71 seconds, related to network 111 with high volume.



(a) High volume



(b) Medium volume



(c) Low volume

Figure 10 Cycle lengths for the two control modes studied: Fuzzy (Fuz) and Fixed-time coordinated (Fix)

Table 7 Average cycle length, in seconds

Volume	Fixed-time coordinated	*Fuzzy*	Difference (%)
High	95.0	64.0	-32.5%
Medium	52.0	46.4	-10.8%
Low	50.0	38.5	-23.0%

Another interesting result that comes from Figure 6 is that the cycle lengths tend to decrease from one network intersection to another, following traffic movement direction along the arterial road. A comparison among the cycle lengths for each network considered is presented in Table 8, where the exceptions to the previously referred trend are highlighted. As Table 8 also shows, the greatest differences occurred to the high volume level.

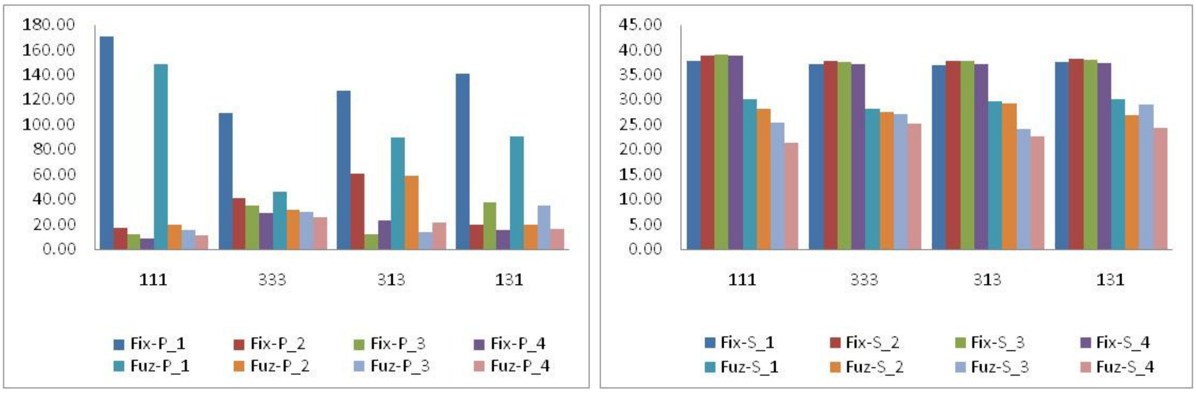
Table 8 Cycle length variations between successive network intersections, in percentage

Network	High Volume			Medium Volume			Low Volume		
	Int2/Int1	Int3/Int2	Int4/Int3	Int2/Int1	Int3/Int2	Int4/Int3	Int2/Int1	Int3/Int2	Int4/Int3
111	-3.98	-5.16	-8.17	-0.41	0.05	-0.85	-0.42	-0.18	-0.47
333	-0.87	-1.81	-3.21	0.05	-0.15	-0.49	-0.24	-0.38	-0.17
313	0.87	-11.30	-3.40	0.12	-0.31	-0.24	-0.14	-0.17	-0.25
131	-6.62	2.93	-7.00	-0.33	-0.12	-0.37	-0.48	-0.17	-0.42

Int2/Int1: Intersection 2 related to Intersection 1.

4.3.2 Traffic performance

The two control modes tested caused similar pattern for average delay to the controlled traffic at the arterial road. This indicates comparable traffic progression characteristics between these modes, which varies according to the network configuration. Figure 11a illustrates this situation for the high traffic volume level. In spite of this, the absolute values are different and, in general, slightly smaller for the fixed-time coordinated control. At the intersection 1 approach, as expected, the traffic random arrivals are better served by fuzzy control.

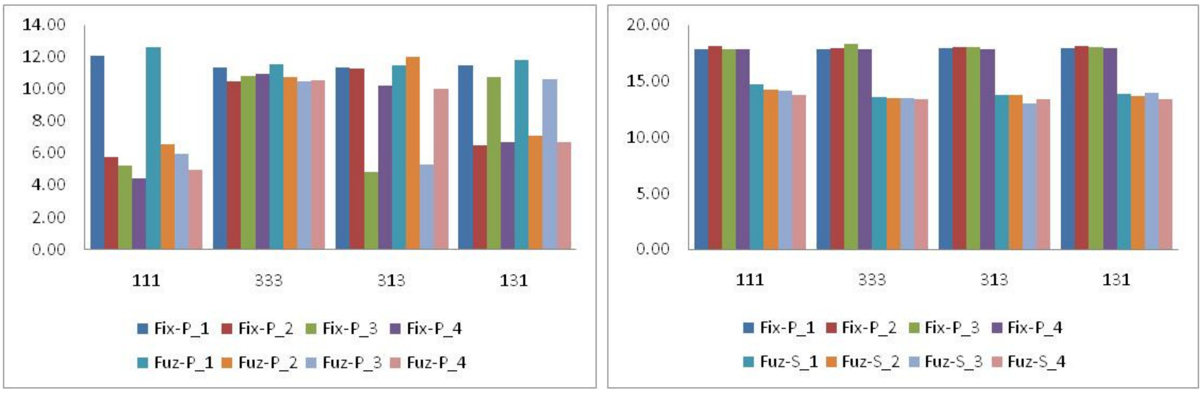


(a) Arterial road (b) Secondary roads

Figure 11 Average delay per intersection approach for high volume under the two control modes studied: Fuzzy (Fuz) and Fixed-time coordinated (Fix)

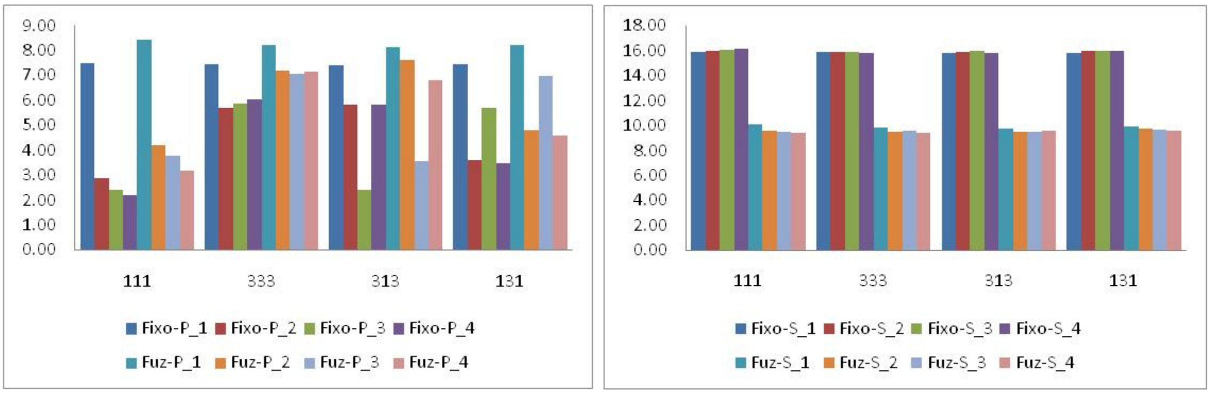
For the secondary roads' approaches, however, the traffic behavior strongly differs between the two control modes. This condition is more evident to the high volume level. As per Figure 11b, the average delays caused by fuzzy control are much smaller than those related to the fixed-time coordinated control. In addition, in fuzzy control, these delays decrease from intersection 1 to 4.

For the medium and low volume levels, the same pattern is observed for the secondary roads. However, while the differences in delay for the high volume (considering the fuzzy control situations) are up to 8.7 seconds, for the other volumes they do not reach 1.0 second (see Figures 12 and 13).



(a) Arterial road (b) Secondary roads

Figure 12 Average delay per intersection approach for medium volume under the two control modes studied: Fuzzy (Fuz) and Fixed-time coordinated (Fix)



(a) Arterial road (b) Secondary roads

Figure 13 Average delay per intersection approach for low volume under the two control modes studied: Fuzzy (Fuz) and Fixed-time coordinated (Fix)

The percentage of stops and number of stops associated to fuzzy control, as related to those of per fixed-time coordinated control, presents similar characteristics of average delay. The complete results of traffic performance analysis can be found in Andrade (2009).

5 - CONCLUSIONS

The simulations conducted in this study considered two signal control modes, which are: fixed-time coordinated, adopted as the reference control; and fuzzy, originally designed to isolated intersection control. The basic objective of the study was to investigate the impact of using isolated fuzzy intersection controllers (isolated FSC) to control an arterial four-intersection network, with no turnings moviments and without adding any special provisions to this type of operation. The analyses took into account three traffic performance measures (average delay per vehicle, percentage of stops, and number of stops per vehicle). The response of isolated FSC was also investigated, by means of the average green time delivered to the intersections' approaches and corresponding average cycle lengths for each intersection. The study was conducted for three volume levels (named high, medium and low), and considers four different network configurations in terms of spacing among the four intersections.

The global network results show that the traffic controlled by isolated FSC performed better than under fixed-time coordinated control, for the majority of the situations studied. For the high volume average delay, the gains were up to 36%. The analysis by road type allows verifying that this benefit of the isolated FSC is due to its positive impact in the secondary roads' delays.

The analysis at the road type level also indicates the adaptive capability of the isolated FSC to respond to platoon movements along the arterial road. Although benefiting this operation not so well as the fixed-time coordinated controllers, the fuzzy controllers assure more equilibrated operation among the traffic of the arterial road vis à vis the traffic of secondary roads. This situation is made clear especially from the average delay results. Therefore, it is possible to conclude that the fixed-time coordinated control benefits more the arterial road, as it was programmed to do so. The fuzzy controllers, however, are able to assure reasonable progression along this road and, at the same time, its intrinsic characteristics of responding on-line to the prevailing traffic at all intersections' approaches, guarantees a more equilibrated operation with all traffic involved.

Another relevant finding of the present work, which corroborates previous studies in the same subject, is that the network configuration significantly affects the fuzzy signal controller operation and, therefore, the performance of the traffic controlled along the arterial road. The exploratory studies also allow for observing the interaction among traffic volume and network configuration in traffic performance.

The overall results of the exploratory studies undertaken in this work clearly show the potential advantages of future research towards introducing control elements for improving the use of isolated FSC for network operations. They also show that any element designed for this purpose must consider the combination of traffic volume and spacing among the network intersections.

Based on the performed studies, it is also recommend that future research should consider more realistic traffic situations as is the case of turning movements at signalized intersections as well as grid networks.

REFERENCES

Andrade, M. and M. A. P. Jacques. (2008a). Comparative study on Mamdani and Sugeno types of controller for signal control at isolated intersections (*in Portuguese*). Transportes (Rio de Janeiro), v. XVI, p. 24-31.

Andrade, M. and M. A. P. Jacques. (2008b). Evaluation of alternative knowledge base structures for fuzzy signal controllers (*in Portuguese*). In: XXII Congresso de Pesquisa e Ensino em Transportes, 2008, Fortaleza. Panorama Nacional da Pesquisa em Transportes 2008. Rio de Janeiro : Anpet, 2008.

Andrade, M. (2009). Studies on fuzzy signal controllers to be applied in open network operations. Doctoral Thesis (*in Portuguese*). Publicação T.TD-02 A/2009, Departamento de Engenharia Civil e Ambiental, Universidade de Brasília, p. 236.

Chiu, S. and S. Chand. (1993). Self-organizing traffic control via fuzzy logic. In: Decision and Control, 1993., Proceedings of the 32nd IEEE Conference on, Vol.2, 15-17, San Antonio, TX, USA, p. 1897-1902.

Gipps, P.G. (1981). A Behavioural Car-Following Model for Computer Simulation. Transportation Research, Vol. 15B(2), p. 105-111.

Gipps, P.G. (1986). A model for the Structure of Lane-Changing Decisions. Transportation Research, Vol. 20B(5), p. 403-414.

Jacques, M.A.P.; J. Niittymäki, and M. Pursula. (2002a). Analysing Different Fuzzy Traffic Signal Controllers for Isolated Intersections. Paper accepted for presentation at TRB 81st Annual Meeting. Washington, DC.

Jacques, M. A. P.; J. Nittymäki; M. Pursula, and I. Kosonen (2002b). Analysis of Different Defuzzyfication Methods Applied to Fuzzy Signal Controller. In: XII Congresso Panamericano de Ingeniería de Tránsito y Transport. Quito, Equador.

Jacques M. A. P.; M. Pursula, J. Niittymäki and I. Kosonen. (2002c).The Impact of Different Approximate Reasoning Methods on Fuzzy Signal Controllers. Proceedings of the 13th Mini-EURO Conference. pp. 184-192.

Jacques, M. A. P., D. B. L. M. Santos, M. Pursula and I. Kosonen. (2005). Importance of Fuzzy Sets Definitions for Fuzzy Signal Controllers. Applied Research in Uncertainty Modeling and Analysis, Chapter 18, pp. 399-416. USA: Springer.

Kim, S. (1994) Application of Petri Networks and Fuzzy Logic to Advanced Traffic Management Systems. Ph.D Thesis, Polytechnic University, USA.

Lee, J-H. e H.L.- Kwang. (1999). Distributed and Cooperative Fuzzy Controllers for Traffic Intersections Group. In: IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews, Vol. 29, No. 2.

Nakatsuyama, M., H. Nakahashi, e N. Nishizuka (1983) Fuzzy Logic phase controller for traffic junction in the one-way arterial road. Proceedings of the IFAC 9th Triennal World Congress, Pergamon Press, Oxford, UK, p. 2865-2870.

Niittymäki, J. (1998). Isolated Traffic Signals – Vehicle Dynamics and Fuzzy Control. Licentiate Thesis. Helsinki University of Technology, Civil and Environmental Engineering, Otaniemi, 128p.

Niittymäki, J. (1999). Fuzzy Logic Two-Phase Traffic Signal Control for Coordinated One-Way Streets. In: IEEE Midnight-Sun Workshop on Soft Computing Methods in Industrial Applications. Kuusamo, Finland. p. 69-74.

Niittymäki, J. and R. Nevala. (2001). Fuzzy Adaptive Traffic Signal Control – Principles and Results. In: Joint 9th IFSA World Congress and 20th NAFIS International Conference, Vancouver, Canada, 6p.

Niittymäki J. (2001) Installation and Experiences of Field Tests of a Fuzzy Signal Controller. In: European Journal of Operational Research, Vol. 131/2. p. 45-53.

Pappis, C. P. e H. Mamdani. (1977) A Fuzzy Logic Controller for Traffic Junctions. In: IEEE Transactions on Systems, Man and Cybernetics. Vol. SMC-7, Nº 10.UnB-Sitracs

UnB-Sitracs (2009). User Manual. Available in <http://sourceforge.net/projects/unb-sitracs/files/>

Vaz, A. M.; E. R. de Oliveira and M. A. P. Jacques. (2005) Impact of membership functions on fuzzy signal controllers' operation: exploratory study (*in Portuguese*). In: XIX ANPET- Congresso de Pesquisa e Ensino em Transportes. V. 1. p. 853-862.