Journal of Transport Literature, 9(4), 5-9, Oct. 2015.

The Journal of Transport Literature

www.journal-of-transport-literature.org

ITPS

International Transport Planning Society

Comparison between common traffic lights and three types of traffic lights with visual cycle – a safety and capacity analysis

Luciana Gasparelo Spigolon[1]; Barbara Stolte Bezerra[2,+]; Jorge Tiago Bastos[1]; Antonio Clóvis Pinto Ferraz[1]; Rosane Aparecida Gomes Battistelle[2]

[1] *University of São Paulo, São Carlos, Brazil*

[2] *State University of São Paulo - UNESP, Bauru, Brazil*

Article Info

Keywords:
before-after study
traffic lights
countdown time devices
traffic safety

Submitted 28 Sep 2014;
received in revised form 28 Jan 2014;
accepted 20 Apr 2015.

Abstract

The objective of this paper is compare the common traffic lights (CTL) to three different types of traffic lights with countdown displays (SCD) and assess their effects on road safety and capacity. This comparison is required because the results found in the literature are divergent among countries and cities, and one of the SCD analyzed in our study is different from the SCD used worldwide. An observational before-after study was conducted to evaluate the safety and capacity in a period of one year before and one year after the implementation of the SCD in three Brazilian cities. The results indicate that the SCD models 1 and 3 had around 35%±14% reduction in the total number of accidents; the model 2, does not have significant reduction. In order to perform the capacity analysis a framework for data collection and an adaptation for estimation of initial lost time in each phase were developed. Considering the capacity analysis there was a reduction around 11% in the lost time in SCD model 1, 7% in SCD model 2 and 3% in SCD model 3. However the implications of this on capacity are trifle due to a small increase in the average headways for all SCD models compare to CTL.

+ Corresponding author. Av. Eng. Luiz Edmundo C. Coube 14-01. Bairro: Vargem Limpa, CEP 17033-360 - Bauru - SP, SP
E-mail address: barbarabezerra@feb.unesp.br

Introduction

The purpose of this paper is to study the effect of three models of traffic lights with visual cycle, currently in use in some Brazilian cities, known as signals with countdown displays (SCD), in comparison to the common traffic lights (CTL), using the naive "before-after" method for safety analysis and comparison group for the capacity and safety analysis. This study became necessary because of the increase in the implementation of this kind of traffic lights (SCD) in median and large cities in Brazil, and due the controversial discussion in the literature about its impact on safety and capacity.

Nowadays, many features are incorporated to the traffic system without proper prior research of their possible effects on safety. An example of a such situation emerged on the pursuit of a solution that was supposed to help drivers to make a decision when they are in the dilemma zone of a signal; thus resulting in a number of operational procedures (such as the flashing signal phase) and devices (such as signal countdown displays). Up to date, these so called solutions have uncertain results on safety and capacity, generating mixed feelings among traffic engineers.

The flashing signal phase has been in use since the 1960's in different variations, being the most common the flashing green phase and the flashing amber with the static green phase alerting drivers a few seconds before the end of the green. Some studies investigated this kind of operation and found an increase of rear-end-collisions frequency due to the incitement of inadequate stopping decisions (Mahalel et al. 1985; Mussa et al. 1996), although in the flashing amber phase they found a reduction of severe decelerations and red-light violations that could reduce right angle collisions. Similar results were found later by Koll et al. (2004) about the green flashing phase in Switzerland. Factor et al. (2012) severely criticized the use of green flashing light due to the great variance in driver's reactions to this operation and the lack of evidence about its safety effects. Anyhow, the positive psychological effect of this kind of operation may have among drivers is not discarded. In recent years signal countdown devices have been used in several cities across the globe. This kind of device could have countdown displays for either the green, amber or red phases. The main allegation about the use of SCD is that it can provide additional information to help drivers to make safe stopping and crossing decisions. Additionally, it would also decrease the lost time in the change of phases and perhaps increase capacity. However, some studies indicate that the start-up lost time can have some reduction (17-32%) although the saturation headway improvements are trifling (Limanond et al. 2009). Nevertheless, the effect on safety of this SCD is still dubious, because the data in literature are controversial. Some researches indicate that the countdown devices could help drivers to make a decision, reduce the red light violations and danger maneuvers during the phase transition (Ma et al. 2010; Long et al. 2013). However, in the same study, Ma et al. (2010) pointed out that the speed can increase for vehicles approaching the amber period, and the study of Lum and Halim (2006) concluded that the analysis of the long term performance of green SCD, stimulates the red-stopping actions when the traffic flow is heavy, but does not have effects in reducing red light violations after six months of operation. Also, there are some differences between the SCD for green and red periods: some researches appointed that SCD for red period has safety benefits and SCD for green periods should be avoided (Chiou and Chang, 2010), because drivers who are approaching the intersection may increase their speed to clear the intersection in the remaining green time.

The most common devices have the display for green and red phases; others have the display only for the green or for the red phase. The device with green countdown displays shows similar results as the green flashing operation (Chiou and Chang, 2010), which are likely to cause an increase on rear-end collisions (since the dilemma zone is increased) and a decrease on right angle collisions (since the late-stopping ratio is reduced). Nevertheless, in Taiwan, a research report (Chen et al. 2007 apud Chiou and Chang, 2010) showed 100% increase in the number of fatal and injured accidents with green countdown display, a 50% decrease with red countdown display, and a 19% increase in devices with red and green countdown displays. From these results, one should recommend authorities to avoid the installation of green countdown, because it might induce driver's aggressiveness to cross the intersection. In this way, the findings of these researches indicate that the red countdown displays can enhance intersection efficiency and are more beneficial regarding traffic safety than the green countdown displays. But still, the evidences are shown for few intersections and just for one year of before and after period.

Due to those controversial findings in literature our research is an attempt to register and analyses the SCD effects on safety and capacity in Brazilian cities, in order to compare the results with other countries, because some authors suggested that the driver's behavior towards SCD could differ among places. Also it was developed an expeditious methodological framework for data collection in field and estimation of the average saturation flow and lost time in each phase, which was reliable and less time consuming if compare with other methods.

The results obtained in our research indicate that the SCD model 1 and model 3 had around 35%±14% reduction in the total number of accidents; the model 2, which is quite similar to CTL, does not have impact on safety. In order to perform the capacity analysis a framework for data collection and an adaptation for estimation of lost time were developed. In the capacity analysis there was a reduction of 10.8% in the lost time of in SCD model 1; 6.8% in SCD model 2, and 2.7% in SCD model 3. However, the implications of this to enhance of capacity are trifle; the results obtained show that all SCD models have higher average headways.

Section 1 presents the research methodology used for this study and the framework for capacity analysis developed. The case study and the analysis and discussion of results are presented in Section 2. In Section 3 are shown the conclusions and contributions of this work, which can be used as hypotheses for further research.

1. Research methodology

This study was conducted in three cities located at the State of São Paulo in Brazil. These cities were chosen because they operate with SCD, they present the same grid pattern in the central area, the same per capita GDP and have a reliable accident data base. Figure 1 show three types of signal with the phase remaining time information, and the common signal used in this study. The CTL is shown in Figure 1a. Model 1 of SCD is used in several cities in Brazil and it has a different design of traffic lights (Figure 1b). Model 2 (Figure 1c) has been recently used in some cities in Brazil. Model 3 is used worldwide, as well as in Brazil (Figure 1d). In model 1 the remaining time is indicated by the position of the green and red focal light that descends from the top. There are six focal lamps for the red and green phase. In the beginning of the green phase, the green focal at the top and the bottom are turned on; then in pre time period the top focal lamp is turn off and the next focal lamp is lit below in a successive movement; with the same pre set time, the bottom lamp is turn on in the end of the green phase finalizing the "descending" green movement; the same procedure is applied to the red phase (Figure 1e). Model 2 has the same operation as CTL but the visual cycle is displayed by five led lamps that are turned on at the beginning of green phase. After a pre set time, the top led lamp is turned off and then the remaining led lamps are turned off in sequence with the same pre set time and the last remains lit until the end of the green phase. The procedure to the red phase is similar. In model 3 the remaining time in seconds for the green and red phases are displayed in a numerical countdown device. All cities under research use the CTL, but while São Carlos uses the SCD model 1, Ribeirão Preto uses the SCD model 2, and Piracicaba, SCD model 3.

(a) (b) (c) (d) (e)

Figure 1: (a) Common traffic light; (b) Traffic light with visual cycle model 1; (c) Traffic Light with visual cycle model 2; (d) Traffic light with visual cycle model 3; (e) Traffic light with visual cycle model 1 operation.

Framework for capacity analyses

The method of capacity analysis was adapted from HCM 2000(Transportation Research Board, 2000) and Akçelik (1981) and the framework for capacity analyses is described hereinafter. According to HCM 2000 and Roess et al. (2004) the headways between successive vehicles are greater until the fourth vehicle in the queue at the beginning of the green phase. In light of this fact, we formulated the following simplified method (Equations 1 to 5) to obtain the time lost at the beginning and at the end of green phase and the average saturation flow. In the beginning of the green phase, the field researcher activated the chronometer and measured the elapsed time of the fourth and tenth vehicle in line, formed until the end of the red phase, when they crossed the retention line. The researcher used only data obtained when no parking maneuvers and no kind of obstruction was observed in the stream flow, and with only cars in the flow stream and with at least ten vehicles in the queue. Thirty cycles are observed in each intersection. The average headway was calculated with the Eq. 1, the average headway of the first four vehicles with Eq. 2, the average saturation flow with Eq. 3, the lost time in the beginning of the phase with Eq. 4, the lost time in the end of the phase with Eq. 5, the total lost time of the phase with Eq. 6, the total lost time in the cycle with Eq. 7, the effective green time in the phase with Eq. 8, the effective green time in the phase with Eq. 9, the capacity per approach per lane with Eq. 10, and the total capacity with Eq. 11. If the saturation flow is similar in all approaches and lanes, Eq. 12 could be used.

$$h_i = \frac{T_4}{4} \quad (1)$$

$$h_n = \frac{T_{10} - T_4}{6} \quad (2)$$

$$s = \frac{3600}{hn} \quad (3)$$

$$\mathrm{Tpi} = 4 * (h_i - h_n) \quad (4)$$

$$Tpf = I - Tu \quad (5)$$

$$Tp = Tpi + Tpf \quad (6)$$

$$TP = \sum_1^k T_{pk} \quad (7)$$

$$Gek = Gk + Ik - Tpk \quad (8)$$

$$Ge = \sum Gek = C - TP \quad (9)$$

$$CAPm = s * Gek / C \quad (10)$$

$$CAP = n * \sum CAPm \quad (11)$$

$$CAP = \frac{C - TP}{C} * s \quad (12)$$

Where:

h_i : Average Headway for the first four vehicles (s)
h_n : Average Headway (s)
T_j: Time elapsed of the last jth vehicle in queue(s)
n: j -4
T_4 : Time elapsed of the 4º vehicle in queue (s)
T_{pi} : Lost time in the beginning of the Green phase (s)
s: Saturation flow per lane (cpe/h)
Tpf: Lost time in the end of the Green phase (s)
I: Intergreen period (Y+ Rt) (s)
Y: Yellow period (s)
Tu:Time elapsed of the last vehicle after the yellow light (s)
Rt: All red period (s)
Tp: Total time lost in each phase (s)
TP: Lost total time in the cycle (s)
Tpk: Total lost time in phase k (s)
Gek: Effective green of phase k (s)
Gk: Real green of phase k (s)
Ik: Intergreen period of phase k (s)
Ge: Effective green of the cycle (s)
$CAPm$: Lane capacity per hour m (veíc/h)
Gek: Effective green of phase k (s)
C: Cycle length (s)

This adaptation for estimation of the lost time in the beginning of the phase and for the average saturation flow proved to be simple and easy regarding to data collection compared with Akçelik (1981) and DENATRAN(1984), with no significant differences on the means (F-test ANOVA on factor based on 95% confidence interval).

The capacity analysis was performed for the CTL and SCD for each city. In each city, three intersections controlled with CTL and three controlled with SCD were used. The intersections are located in the central area, have same geometric characteristics, similar traffic vehicle flow and their signals operate with two phases.

Safety analysis method

The safety analysis was performed using an observational study before and after implementation of the traffic lights. Two methods were used. The first method is the Naive Before and After Study described in Hauer (1997). The second method is the Comparison Group also described in Hauer (1997). In the first method, it was used the number of accidents one year before and one year after the replacement of the CTL by the SCD in six intersections in São Carlos and Ribeirão Preto, and seven in Piracicaba. In the second method, comparison group (CG), the central idea was to identify a group of entities (streets, intersections, and etc.) that remained untreated, but had similar characteristics to the treated ones, and compare the safety of both. The treated entities form the "treatment group". The untreated entities form the "comparison group". The analysis using the CG was performed in six intersections controlled with SCD and four intersections controlled with CTL (CG) in São Carlos, six intersections with CTL and five intersections with CTL (CG) in Ribeirão Preto using data from one year before and after. In Piracicaba, it was not possible to find a suitable comparison group and this analysis was not performed. For considerations regarding the methodology to find a CG it is suggested consulting Hauer (1997).

2. Results and Discussion

2.1. Capacity Analysis

The results for the average capacity are shown in Table 1. The results obtained in the field for the average headway, initial lost time and final lost time are shown in Table 2.

In accordance with the results obtained it is possible to infer the following regarding the operational performance of SCD: the headway at the intersections with the three SCD models are slightly higher than CTL's; 2% for model 1; 4% for model 2, and 3% for model 3; the lost time in the beginning of the green phase is slightly lower than that of CTL; around 12% less for model 1 and model 2, and 3% less for model 3, and this can be explained by the warning of the end of the red phase leading the drivers to lost less time on departure; also, the lost time in the end of the green phase is slightly lower than CTL's; around 9%, 7% and 3% less for model 1, 2 and 3 respectively, which suggests that drivers are using the intergreen period and perhaps over speeding in the end of the green phase; in this way the total lost time in SCD is lower than that of CTL; around 11%, 10% and 3% less for model 1, 2 and 3 respectively. Regarding the capacity, due to an small increase of the headway in the SCD models, it is slightly reduced by -0.6% for model -1, 1.6% for model 2 and -2.4% for model 3.

Table 1. Results obtained for the average capacity analysis

Parameter	São Carlos		Ribeirão Preto		Piracicaba	
	CTL	SCD model 1	CTL	SCD model 2	CTL	SCD model 3
Cycle (s)	80	80	60	60	100	100
Nº of phases	2	2	2	2	2	2
Headway (s)	2.18	2.23	2.10	2.18	2.10	2.16
Initial lost time per phase (s)	3.09	2.72	3.33	2.94	3.08	2.98
Final lost time per phase (s)	2.07	1.88	1.02	0.96	3.00	2.92
Lost time per phase (s)	5.16	4.60	4.35	3.90	6.08	5.90
Total lost time cycle(s)	10.32	9.20	8.70	7.80	12.16	11.80
Capacity (cpe/h)	1438	1429	1466	1437	1506	1470
Relative difference (%)	-0.63		-1.64		-2.39	

Also the saturation headway for intersections controlled with the CTL and SCD in the three cities is not statistically different, as can be seen in Table 2 (F-test ANOVA one factor, based on 95% confidence interval). In this way, it is not possible to say if there are differences between the type of traffic lights with and without countdown timers in each city. The similarity of results occurs only for the start up lost time as shown in Table2 (F-test ANOVA one factor, based on 95% confidence interval). Thus, in this study we can infer that no significant difference is obtained with the operation of the SCD instead of CTL.

Table 2. Result of F-tests checking the significance of the difference in the mean saturation headway and the start-up lost time

City	CTL		SCD		Different Variance?*	F-Stat.	p-value
	id	Headway ± σ	id	Headway ± σ			
São Carlos (SCD model 1)	1	2.35±0.10	4	2.34±0.45	no	1.142	0.354
	2	2.07±0.26	5	2.21±0.19			
	3	2.13±0.14	6	2.15±0.24			
Ribeirão (SCD model 2)	1	2.04±0.38	4	2.18±0.36	no	0.918	0.482
	2	2.10±0.25	5	2.13±0.49			
	3	2.17±0.22	6	2.23±0.33			
Piracicaba (SCD model 3)	1	1.95±0.16	4	2.06±0.10	no	1.662	0.169
	2	2.04±0.34	5	2.16±0.32			
	3	2.32±0.24	6	2.26±0.31			
	id	Tpi ± σ	id	Tpi ± σ			
São Carlos (SCD model 1)	1	2.83±0.55	4	2.49±0.55	No	1.031	0.412
	2	3.41±0.54	5	2.80±0.67			
	3	3.02±0.66	6	2.86±0.57			
Ribeirão Preto (SCD model 2)	1	3.33±0.60	4	3.33±0.84	No	2.057	0.128
	2	2.95±0.77	5	3.06±0.65			
	3	3.70±0.71	6	2.42±0.22			
Piracicaba (SCD model 3)	1	3.08±0.58	4	3.08±0.44	No	1.395	0.294
	2	3.00±0.11	5	3.16±0.43			
	3	3.16±0.21	6	2.69±0.64			

* Results from Levene's test for equality of variance at 95% confidence interval.

2.2. Safety Analysis

The results obtained from the Before and After Naive Study and for the Comparison Group (CG) are shown in Table 3. The estimative for São Carlos for the naive approach is a reduction in the number of accidents of 34% ± 14% on the six intersections where the CTL were replaced by SCD. In Ribeirão Preto, no safety effect could be detected because the standard deviation in the sample was high (5% ± 22%). In Piracicaba, the estimative indicates a reduction of 35% ± 14% in the number of accidents (with the same range that occurred in São Carlos).

Table 3. Results for the Before and After Naïve Study and CG

	BA Naive			CG		
	São Carlos	Rib. Preto	Piracicaba		São Carlos	Ri. Preto
$\hat{\lambda}$	37	36	37	$\hat{\lambda}$	37	36
$\hat{\pi}$	55	37	56	$\hat{r}_T = \hat{r}_C$	1.12	1.06
$V\hat{A}R\{\hat{\lambda}\}$	37	36	37	$\hat{\pi}$	61.60	39.39
$V\hat{A}R\{\hat{\pi}\}$	55	37	56	$V\hat{A}R\{\hat{\lambda}\}$	37	36
$\hat{\delta}$	18	1	19	$V\hat{A}R\{\hat{r}\}/r_T^2$	0.08	0.06
$V\hat{A}R\{\hat{\delta}\}$	92	73	93	$V\hat{A}R\{\hat{\pi}\}$	362.62	140.65
$\hat{\theta}$	0.66	0.95	0.65	$\hat{\delta}$	24.60	3.39
$V\hat{A}R\{\hat{\theta}\}$	0. 019	0. 047	0.018	$\hat{\theta}$	0.55	0.84
$\hat{\sigma}\{\hat{\lambda}\}$	6.08	6	6.08	$\hat{\sigma}\{\hat{\delta}\}$	20.00	13.29
$\hat{\sigma}\{\hat{\pi}\}$	7.42	6.1	7.48	$\hat{\sigma}\{\hat{\theta}\}$	0.18	0.26
$\hat{\sigma}\{\hat{\delta}\}$	9.59	8.54	9.64			
$\hat{\sigma}\{\hat{\theta}\}$	0.14	0.22	0.14			

π: Expected number of accidents of a specific entity, in a period "after" if it had not been treated; what it has that to be predicted.
λ:. Expected number of accidents of the entity treated in the period "after", is what it has that be estimated.
δ: Reduction of the expected number of accidents in the "after" period.
θ: Ratio between λ and π ("effectiveness index").
rc: ratio between the accident counting in before and after period for comparison group.

rT: ratio between the accident counting in before and after period for treatment group.
ω: ratio between rc and rT.

Using the CG method, the estimative was a reduction of around 45% ± 18% in the total number of accidents in São Carlos. In Ribeirão Preto the estimative was a reduction of 16% ± 26%, but this result is compromised by the high value of the standard deviation and could, therefore, be considered inconclusive according to Hauer (1997).

Conclusion

The objective of this paper was reached since the study obtained the effect of three types of traffic lights with countdown displays that are currently in use in three Brazilian cities in comparison to the common signal, using the naive "before-after" method for safety analysis and comparison group for the capacity and safety analysis. Also it is present a framework for data collection of lost time and saturation flow which proved to be expeditious. The results for safety analysis showed that the SCD model 1 and model 3 had around 35%±14% of reduction in the total number of accidents (naive method); model 2, which is quite similar to CTL, does not have an impact on safety. Regarding the capacity analysis it was found a reduction in the lost time of 10.8% in SCD model 1, 6.8% in SCD model 2 and 2.7% in SCD model 3, however this reduction did not have impact in the capacity.

The results obtained in this study should be seen with discretion, because it is not possible to categorically declare any effective reduction or increase in the number of accidents after the implementation of signals with visual cycle or countdown display, although the before and after naive approach showed significant reduction for models 1 and 3. These findings are in accordance with the studies of Chiou and Chang (2010), however in disagreement with the results obtained by Chen et al. (2007) and apud Chiou and Chang (2010), which indicates some level of setback regarding road safety. Nonetheless, Long et al. (2013) showed that the countdown devices might assist drivers to make a decision in the dilemma zone and reduce the danger during the phase change. Empirical evidences with drivers in this research point out that they prefer the SCD, because they are more conspicuous.

In relation to the capacity analysis the results are in accordance with the studies of Chiou and Chang (2010), Liamanond et al. (2009), Beck et al. (1996), Ma et al. (2010), this is, the lost time is reduced with SCD, but the capacity is minimally enhanced. In our case, the capacity is insignificantly reduced, because in all SCD models the average headways are slight higher than that of the CTL model.

Also in this study no substantial difference was found among the three types of SCD studied regarding the variance for the headways and lost time. Thus we can infer that the three SCD models do not have difference regarding the capacity if compared with common traffic lights. Model 1 causes some confusion in the first days of operation, due to its unusual shape, although captures the attention of drives because of its visual impacts. Nevertheless, theoretically, the uniformity of traffic signals devices is very important because drivers might misunderstand devices that are different and this might lead drivers to react oddly and cause an accident. Therefore, the psychological effects on drivers of this device must be assessed. Further studies must be performed, since the results are not conclusive about the impact on safety of the use of SCD against CTL. In order to improve this study the authors, in a future work, intend to: include more intersections and years; observe both type and number of conflicts in each type of traffic light; and count the number of vehicles running red light in each type. This last point is very important to be examined since empirical evidences show that drivers tend to over speed more in the yellow period in SCD than in CTL, although it is still pure speculation in our study, but is corroborated by Ma et al. (2006).

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