Empirical analysis of the impact of signal head locations on driving behavior

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The empirical study was conducted at the T-junction including near and far side signal head designs in Tashkent, Uzbekistan. The analysis consists of start-up as well as stopping and crossing decision-making in terms of safety and performance. Overall, results of start-up analysis display that locating the signal at the near side leads to safer conditions, namely less red light running rate, improper stopping-crossing decisions and misleading inside the signalized intersection. In contrast, the far side design tends to decrease the lost time and increase the intersection performance for 4.7%.

Key words: near and far side traffic lights, arrival and departure side traffic lights, start-up behavior, stopping and crossing decision-making.

1. INTRODUCTION

The importance of design and operation of signalized intersections have been discussed for decades in terms of safety, efficiency and ergonomics all over the world. It has been declared that approximately 40% of road incidents, 80% of traffic delays and about 20% of total vehicle emissions are generated at the signalized intersections[4)].

In the globe, the design and location of signal head is based on the experience and understanding of traffic management in each country separately. Basically, it is called as the “near side” design if the signal head is located at the arrival side of the signalized intersection, and the “far side” design if it is at the departure side, as shown in **Fig. 1**. The combination of both far side and near side is the case in some countries as well.

Notwithstanding the beliefs and preferences in signal head location of traffic engineering practitioners in different countries, there is not a common opinion to the impact of traffic lights design on safety, capacity and ergonomics.

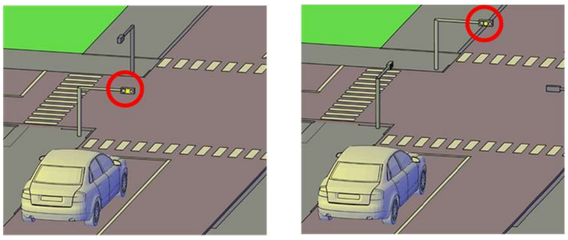


Fig.1 Near and far side designs of signal head locations.

Duarte and Corben[2)] stated that far side traffic lights can result in an incorrect perception of the stop line, which becomes an issue at the crossing decision-making processes. Long and Nitsch[3)], studied the effects of dead turnings on driver’s perception reaction time at passive railroad crossings, declared that it takes 0.7 s for the driver to turn the head one way and 1 s to turn it back if the object is more than 15° from the driver’s sightline. Based on research of Long and Nitsch[3)], it can be interpreted as far side traffic lights to be more efficient in the subject of start-up behavior or perception reaction time reduction in stopping and crossing decisions.

The Manual of Uniform Traffic Control Devices[4)] supports the idea that the far side traffic lights design creates conditions of less late yellow and red light running occurrence.

Additionally to above mentioned ideas, it is known that the placement of the signal head at the far side leads to signal phase limitations, in other words it is unsafe to have different green light durations for opposite directions of the same approach since it can lead to misunderstanding of the right to turn. The complexity of such a condition arises due to the fact that far side design drivers see the signal inside intersection and have an opportunity to start movement mistakenly referring the green phase end of their direction whereas near side drivers do not see the signals inside the intersection and have to wait until opposite flow stops. Moreover, the condition of the far side signal head is seen while crossing the signalized intersection may urge crossing drivers with a rather low approaching speed to stop inside the intersection after the signal change due to decision change.

Recently the driving simulator study of drivers' behavior at the yellow onset of the signalized intersection was conducted by Matsuda et al.[4)] As a result of the stopping and crossing decision-making analysis, it was observed that locating the signal head at the near side of the intersection resulted in higher proportion of the drivers who decided to pass the intersection at the yellow onset than in case of far side design. Additionally, it was found that the Perception Reaction Time was slightly longer in case if the signal head was located at the near side.

The behavior of drivers at the signalized intersection is a complex process where each driver makes a personal decision based on plurality of conditions such as traffic, speed, the size of intersection, signal timing and so on. Overall, behavior of drivers' can be reflected in start response time at the start-up, when the light changes to green, or in approaching speed, acceleration and deceleration rates, perception reaction time in stopping and crossing decision-making at the yellow onset prior to red light, when the driver has to decide whether to cross the intersection or to stop in front of the stop bar.

The objective of this study is to compare near and far side designs in case of safety and efficiency based on the results, observed during empirical study.

2. FOCUS OF THE ANALYSIS

This study focuses on the following drivers' behaviors, which are expected to have some impacts by the signal head locations:

(1) Start-up behavior.

In start-up analysis such parameters as start response time, time to stop line and headway of the first and second vehicles are assumed to be the major factors distinguishing the behavioral differences of near and far side signal head locating.

Start response time (SRT) is the time interval from the onset of green light to the instant when a vehicle starts to react to pushed accelerator pedal[6)].

Time to stop line (TTSL) is a parameter, which reflects the necessary time to approach the stop bar right after the start response time, as soon as vehicle starts movement. If the driver occasionally crosses the stop line at the stopping decision then in the start-up analysis TTSL is considered to be "0".

Headway of the 1st vehicle is the time between green light start and the instant when the vehicle crosses the stop line[7)]. If the driver occasionally crosses the stop line at the stopping decision then at the start-up analysis the Headway of the 1st vehicle is the time between green light start and the instant when the vehicle starts to move.

Headway of the nth vehicle (n>1) is a time in seconds, between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles[8)].

Saturation headway is the average headway between vehicles occurring after the fourth vehicle in the queue and continuing until the last vehicle in the initial queue clears the intersection[8)].

Lost time is the time in seconds, during which an intersection is not used effectively by any movement[8)].

Start-up lost time is the additional time, in seconds, consumed by the first few vehicles in a queue at a signalized intersection, above and beyond the saturation headway, because of the need to react to the initiation of the green phase and to accelerate[8)].

The red light running rate is calculated through the proportion of drivers crossed the intersection after the onset of red light to the sum of those who crossed the intersection during the yellow light and first stopping drivers.

(2) Stopping and crossing decision-making.

Speaking about decision-making processes at the yellow onset, typically two decisions are considered, stopping and crossing.

The distances needed for crossing the intersection within yellow light and for stopping of the moving vehicle are equated as follows:

$$Xc = vY + \frac{1}{2}a_2(Y-\tau)^2 \quad (1)$$

$$Xs = v\tau + \frac{v^2}{2a_1}, \quad (2)$$

Where, Xc: crossing distance, Xs: stopping distance, v: approaching speed, Y: yellow interval, τ: perception-reaction time, a_1: deceleration rate, and a_2: acceleration rate.

Based on Gazis et al.[9], it can be deduced that stopping and crossing decisions altogether give four outcomes within yellow light, as shown in **Table 1**. Based on abovementioned parameters, 4 zones are considered, as shown in **Fig. 2**.

Furthermore, it is important to emphasize that a driver's behavior at the yellow onset is dependent on variations of factors. Horst[10] in 1988 stated that than more time passes after the yellow onset than higher the probability of stopping decision. Moreover, the speed level and the distance to the stop line (DTSL) are highly important factors as well. Thus, Yang et al.[11] observed that at high speed level and close distance to the stop bar the probability of crossing decision increases significantly.

(3) Capacity.

Capacity is affected by the start-up behavior that determines the start-up lost time as well as the stopping and crossing decision-making that determines the clearance lost time. Thus, this study considers these combined impacts on the capacity in order to evaluate efficiency in the cases of near and far side signal heads.

Table 1. Conditions at the onset of yellow.

Decision	Distance to the stop line	
Stopping	Less than stopping distance	More or equal to the stopping distance
Crossing	Less than crossing distance	More or equal to the crossing distance

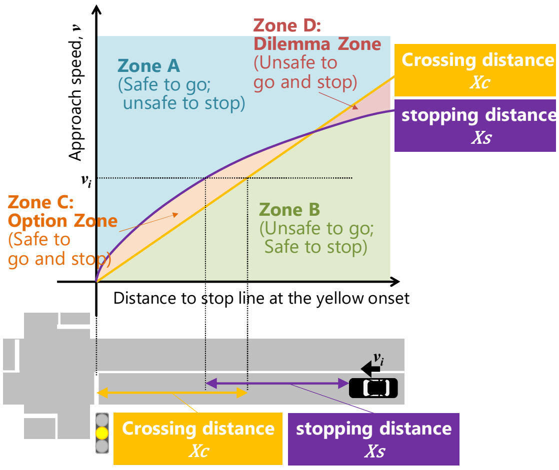


Fig. 2 Drivers decision-making at the yellow onset.

3. RESEARCH METHOD.

(1) Data collection

As the most ubiquitous and affordable way of traffic flow data collection, which were also used in a number of previous studies[12)-16)13)], video recording and data extraction were conducted in this study.

Video recording was conducted at the T-junction in Tashkent, Uzbekistan in the daytime in August 2019. Note that the crossing road at the T-junction does not have signal head and operated based on priority rule, whereas traffic signals are installed and operated for the crosswalks.

The intersection has both conditions near side and far side, with 4 m and 15 m between stop line and signal pole accordingly. As illustrated in **Fig. 3**, the traffic flow was recorded on 3 cameras per each approach, 5.5, 30 and 52.5 m as well as 5.5, 25 and 53.5 m to the stop line in near and far side designs respectively. Each case included an additional camera for traffic lights timing recording. All cameras were synchronized with each other.

Signal timing consist of 15 s of green light, 4 s of flashing green light, 3 s of yellow light, 30 s of red light as well as 3 s of warning red with yellow light prior to green phase.

Traffic flow during data collection was under-saturated, varied between 300 to 600 vehicles per hour per lane both for near side and far side signal location designs. The capacity of T-junction is approximately 720 vehicles per hour per lane both for near side and far side designs in consideration with recommended headway of 1.895 sec for passenger cars in MUTCD[11)].

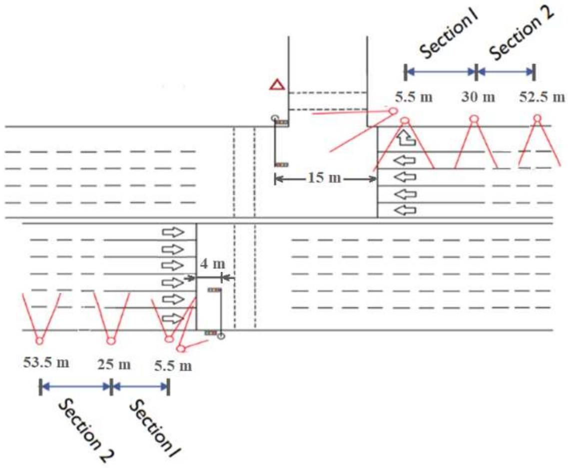


Fig. 3 Data collection area map.

Overall, in start-up analysis, 100 vehicles of 2nd and 3rd lanes were observed for start response time, time to stop line and headway of the first vehicle as well as 73 and 89 vehicles for headway of the 2nd vehicle in near and far side designs accordingly. To analyze stopping and crossing decisions, we observed 78 stopping and 98 crossing decisions in near side design as well as 67 stopping and 117 crossing decisions in far side design. Here, only passenger vehicles, which entered the area of 53 m to the stop bar during the yellow light, were considered for crossing while the first stopping vehicles after the onset of yellow light of each cycle was considered for stopping decision.

(2) Data processing

The time to red light (TTRL) is based on signal change at each cycle. Since TTRL = 0 was considered to be the onset of red, the onset of yellow was accepted as "-3" s. The same approach was conducted for the start-up analysis, where the onset of green after red with yellow light was considered to be the "0" point.

Vehicle speed was calculated based on the length of each vehicle (referring the information provided by car manufacturers) and the reference line at the road. As an example, **Fig. 4** depicts the reference point 52.5 m of far side design. Based on the facts that 30 frames duration represents 1 s, it is possible to define how many frames it takes to pass the reference point and to obtain the vehicle speed by the following formula:

$$V = \frac{l}{n_f/30} \cdot 3.6 \tag{3}$$

Where, V: vehicle speed (km/h), l: vehicle length (m) and n_f: quantity of frames spent for the vehicle to pass the reference point from its head to rear end (can be fractional, if not integer).

The acceleration and deceleration of the vehicle were calculated based on the vehicle speeds at the two reference points, assuming the constant acceleration/deceleration within the section between these two points.

The section 1 is between 5.5 − 25 m and 5.5 − 30 m, the section 2 is 25 − 53.5 m as well as 30 − 52.5 m for near and far side signal head locations respectively.

$$a_i = \frac{\Delta v}{\Delta t} + g \sin\alpha \tag{4}$$

Where, a_i: deceleration rate (m/s^2) (if i=1) or acceleration rate (m/s^2) (if i =2), Δv : speed difference at the section 1 and 2, Δt : time to red light (TTRL) difference at the section 1 and 2. Here,

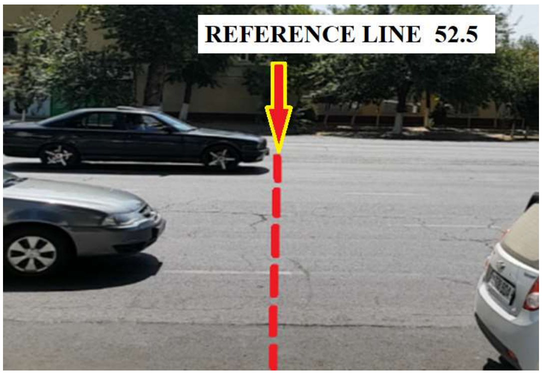


Fig. 4. The example of speed calculation.

Table 2. Road profile parameters.

	Section 1	Section 2
Far side	-0,4%	-0,3%
Near side	0,8%	0,8%

the second term was added in order to compensate the acceleration/deceleration rate, because the road profile is slightly inclined with the descent at the downstream of the far side and ascent of the near side approach, as depicted in **Table 2**. This term was determined in accordance with the second Newton Law:

$$F = m \cdot a \tag{5a}$$

$$\therefore a = \frac{F}{m} = \frac{m \cdot g \cdot \sin(\alpha)}{m} = g \cdot \sin(\alpha) \tag{5b}$$

Due to the limitation of the available positions to set the cameras, the vehicles could not be always recorded at the yellow onset. Therefore, the position to the stop bar, approach speed, and acceleration/deceleration rates of the vehicles were estimated for the comparison analysis, where each vehicle was analysed at the points of 53, 27.5 and 5.5 m to the stop bar for the near and far side designs. The points of 53 and 27.5 m to the stop bar were modelled based on actual time to red light and speed of points 53.5 and 25 m as well as 52.5 and 30 m and average acceleration/deceleration values of section 1 and 2 in near and far side designs accordingly. The same concept was used to define the vehicle position at the yellow onset (TTRL = -3 s).

4. RESULTS.

(1) Start-up behavior analysis.

Table 3 displays the statistics of start-up behaviors. Due to predominantly warned state of drivers by the 3 second of red with yellow light prior to the green phase, the start response time (SRT) and headway of the first vehicle do not

Table 3. Summary of the start-up behaviors

Subject	SRT (s)		TTSL (s)	
Signal head	Near	Far	Near	Far
Mean	-1.13	-0.98	1.31	1.10
STDV	0.98	0.86	0.66	0.56
Min.	-2.63	-2.40	0.00	0.00
Max.	1.70	1.60	2.87	2.37
P value (0.05)	26.3%		2.0%	
Subject	Headway (s)			
	1st vehicle		2nd vehicle	
Signal head	Near	Far	Near	Far
Mean	0.21	0.11	2.98	2.73
STDV	-2.33	-2.30	1.43	1.43
Min.	3.30	3.03	4.43	4.50
Max.	1.17	1.12	0.65	0.68
P value (0.05)	64.7%		2.1%	

display statistical difference with the significance level of 0.05. However, we observe statistically different behavior in time to stop line (TTSL), meaning that it takes significantly more time for the driver to approach the stop line in the case of the near side signal head location.
Similar state was observed in the headway of the 2nd vehicle where the far side design displays faster reaction with the statistical significance level of 0.05. Overall, we observe significant difference of drivers' behavior at the start-up with the slower reaction in case of the near side traffic lights placement.

(2) Stopping and crossing decision analysis.

In stopping and crossing decision analysis the most important and impacting factors are considered to be speed and time to red light. Having evaluated speed and TTRL in **Table 4 and 5**, it was observed that the data sets of near and far sides are not statistically different with the significance level 0.05. It is obvious that drivers of near and far side signal designs encountered similar conditions both in stopping and crossing decisions. Thinking about behavior of crossing drivers, we see similar slight speed increase as approaching the intersection in both conditions.

As for stopping decision, we observe a different behavior starting with statistically insignificant speed difference at the point 53 m to statistically significant speed difference with the significance level 0.05 at the point of 5.5 m to the stop bar. The explanation of such a phenomenon is in two factors: the far side drivers push accelerator harder and the near side drivers tend to start farther from the stop bar, supposedly to have better visibility of the signal head.

Another important observation of far side

Table 4. Conditions of crossing drivers

		TTRL (s)		Speed (km/h)	
Distance		Near	Far	Near	Far
5.5 m	Mean	-1.72	-1.80	54.2	53.4
	STDV	1.26	1.26	11.0	12.6
P value (0.05)		76.7%		62.0%	
27.5 m	Mean	-3.27	-3.37	53.5	51.8
	STDV	1.37	1.40	12.4	13.4
P value (0.05)		60.8%		34.3%	
53 m	Mean	-5.17	-5.37	52.0	49.3
	STDV	1.78	1.83	13.8	15.5
P value (0.05)		41.5%		18.6%	
		Acceleration (m/s^2)			
Signal head		Near		Far	
Section 1	Mean	0.13		0.22	
	STDV	0.63		0.59	
P value (0.05)		31.2%			
Section 2	Mean	0.25		0.26	
	STDV	0.43		0.57	
P value (0.05)		89.6%			

Table 5. Conditions of stopping drivers

		TTRL (s)		Speed (km/h)	
Distance		Near	Far	Near	Far
5.5 m	Mean	1.10	0.32	11.6	15.0
	STDV	1.95	1.82	4.7	4.7
P value (0.05)		1.6%		3E-03%	
27.5 m	Mean	-2.30	-2.57	35.3	38.9
	STDV	1.73	1.74	10.1	5.9
P value (0.05)		35.8%		0.8%	
53 m	Mean	-4.60	-4.79	47.0	46.4
	STDV	2.04	1.99	10.1	10.7
P value (0.05)		27.1%		71.8%	
		Acceleration (m/s^2)			
Signal head		Near		Far	
Section 1	Mean	-2.07		-2.33	
	STDV	0.80		0.70	
P value (0.05)		4.4%			
Section 2	Mean	-1.49		-1.15	
	STDV	0.85		0.99	
P value (0.05)		3.0%			

stopping drivers, as it was mentioned above, was higher variation of deceleration between sections 1 and 2 in comparison with the near side case. Comparing deceleration variations, the datasets are statistically different with the confidence level of 0.05. Moreover, it can be said that near side signal head location drivers display much smoother and more confident stopping behavior at the section 1 and 2.

As it is displayed at **Fig. 5 and 6**, one of the most striking features was an unusual deceleration behavior of crossing drivers at the distance of 27.5 m to the stop bar.

The average speed of the drivers who decided to cross while decelerating were 60.3 and 53.8 km/h

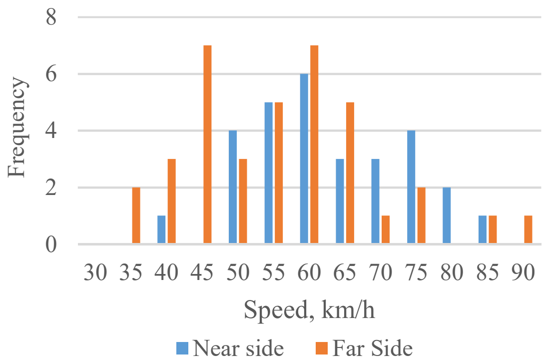


Fig.5. Speed of decelerating crossings at 27.5 m.

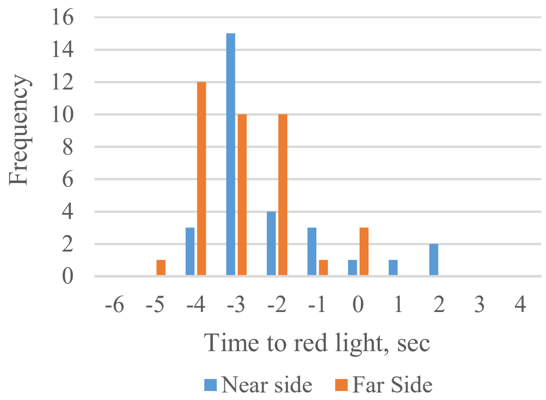


Fig.6. TTRL of decelerating crossings at 27.5 m.

Table 6. Distance to stop line at the yellow onset.

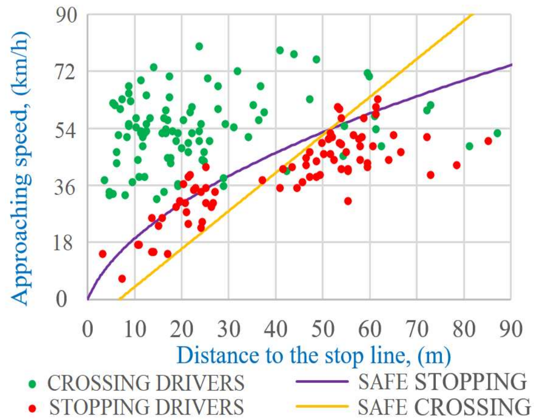
Decision		Near side	Far side
Cross	Mean	24.9	24.4
	St dev.	20.0	22.3
P value (0.05)		84.7%	
Stop	Mean	41.9	34.3
	St dev.	19.3	19.5
P value (0.05)		2.1%	

in near and far design accordingly, which are statistically significant with the confidence level of 0.05.

Furthermore, decelerating drivers tend to be 2.82 s and 3.29 s to the red light at the position of 27.5 m. Such an abnormal TTRL difference can be explained by difficulties of perception of the stop bar location and possibility to pass the stop line before the onset of red light.

The red light running results show that 8.0% of near side design drivers make a decision to cross the intersection at the red light while 8.7% of far side design drivers do so.

In **Table 6**, the distance to the stop line at the yellow light for near and far side signal head location are indicated. First of all, it would be unfair not to mention similar distribution of DTSL in case of crossing decision, 24.4 and 24.9 m respectively. However, the stopping behavior



	Zone A	Zone B	Zone C	Zone D
Cross	**87.8%**	**10.2%**	**2%**	**0%**
Stop	**14.1%**	**55.1%**	**28.2%**	**2.6%**

Fig.7. Near side design dilemma zone analysis.

	Zone A	Zone B	Zone C	Zone D
Cross	**84.6%**	**10.3%**	**2.6%**	**1.7%**
Stop	**44.8%**	**25.4%**	**28.4%**	**1.5%**

Fig.8. Far side design dilemma zone analysis.

displays statistically significant difference with 0.05 confidence level of 41.9 and 34.3 m to the stop bar in case of near and far designs accordingly. Such a difference affirms that the near side signal location tends to be safer from the perspective of red light running since drivers display a tendency to stop being farther from the stop line than far side case.

The main concept of dilemma zone analysis is to define whether the decision-making of the driver is safe or not and if the duration of the yellow time is enough to compensate the approaching speed and perception reaction time variation. In dilemma zone conditions, the pivotal factors for the driver whether to stop or cross are approaching speed and distance to the stop line at the yellow onset.

The parameters to define a safe stopping and crossing distances were 1 s of perception reaction time, acceleration rate of 1.5 m/s2 (maximum acceleration observed in data set) and maximum recommended safe deceleration rate of 3.04 m/s^2.[8)]

Having observed **Fig. 7 and 8**, it is important to make an emphasis on the fact that the behaviors of crossing drivers of near and far side designs are highly similar. 10.2% of near side signal head location drivers display unsafe actions by the crossing the intersection at the state of improper speed and DTSL combination. As it is displayed at **Fig. 8**, 12.0% of far side signal head location drivers behaved similarly.

However, we observe completely different picture at the behavior of stopping drivers. In the case of near side design approach, as shown in **Fig. 7**, the dataset displays 16.7% of drivers, who decided to stop, being at a rather high speed and close distance to the stop bar by the hard and unsafe deceleration. As for far side design approach, as **Fig. 8** shows, 46.3% of drivers decided to stop at the state of improper speed and DTSL combination.

Overall, we observe that the placement of signal head at the near side of the signalized intersection result in the conditions of safer decision-makings with higher proportion of crosses and stops at the proper approaching speed and DTSL combination.

(3) The capacity analysis.

The intersection efficiency is analyzed through the analysis of start-up as well as stopping and crossing behaviors at high demand conditions. The main factors to be analyzed are headways of the first and second vehicles, the timing of the last vehicle to cross the intersection at the yellow onset as well as intersection lost time.

Given the Overall, we observe that the placement of signal head at the near side of the signalized intersection result in the conditions of safer decision-makings with higher proportion of crosses and stops at the proper approaching speed and DTSL combination.

Given **Table 7**, which represents average headways and lost time of 50 groups of the first five vehicles at the 2^{nd} and 3^{rd} lanes. Based on the data, it is obvious that at the condition of high demand, the far side design displays better results of the headways, especially the headway of the first vehicle, which is statistically different with the significance level of 0.05. Additionally, the STDV is smaller in case of far side design for the headways of the 1^{st}-5^{th} vehicles therefore narrower data variance is observed. Furthermore, the lost time in case of near side signal location is higher for 0.66 s per cycle than the placement at the far side, which represents the difference of performance for 4.7%, from 663 veh/hour/lane to 695 veh/hour/lane in case of near and far side respectively.

Table 7. Performance at high demand.

	Headway (s)			
	1st vehicle		2nd vehicle	
	Near	Far	Near	Far
Mean	0.52	-0.06	2.92	2.76
STDV	1.26	1.00	1.15	0.78
P value (0.05)	1.3%		23.5%	
	3rd vehicle		4th vehicle	
	Near	Far	Near	Far
Mean	2.21	2.04	2.04	2.01
STDV	1.11	0.84	1.08	0.93
P value (0.05)	10.5%		76.4%	
	5th vehicle			
	Near	Far		
Mean	1.95	1.92		
STDV	1.12	0.98		
P value (0.05)	78.3%			
	Last to cross (s)		Lost time (s)	
	Near	Far	Near	Far
Mean	-1.34	-1.38	4.21	3.55
STDV	1.25	1.25	0.94	1.09
P value (0.05)	80.4%		0.4%	

5. CONCLUSION.

This study presented results of drivers' behavior comparison impacted by the near and far side signal head locations. The results of start-up and stopping and crossing behavior confirmed that near side traffic lights lead to safer operation of the signalized intersection by means of adequate stopping and crossing decisions, less red light running rate and better stop line perception conditions. However, the locating of the signal pole at the near side tends to better performance of the signalized intersection due to the fact that far side drivers react faster to the signal change and stop closer to the stop bar, which significantly decreases the lost time.

The limitation of this research is in the fact that the signal timing map includes warning stages of flashing green prior to yellow light as well as red with yellow light prior to the green phase. Such warnings inform drivers in advance, which complicates the understanding of perception reaction time and start response time since drivers are aware about the signal change in advance. The future works of this study should include the analysis of signal change unexpectedness in conditions of near and far side signal head locations.

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