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Keywords: LiDAR Sensor, Signalized Intersections, Green Time Allocation, Delay Time, Microsimulation, AIMSUN Software



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Article

Efficiency Improvement at Signalized Intersections: Investigating Smart Green Time Allocation with Two LiDAR Sensors and AIMSUN Microsimulation

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Abstract: As urban populations continue to grow, efficient traffic management becomes paramount in reducing congestion, enhancing air quality, and improving overall quality of life. This study addresses the critical issue of intersection efficiency through the implementation of smart green time allocation strategies at a signalized intersection equipped with two LiDAR sensors. This research aims to investigate optimal green time allocations provided by two LiDAR sensors and analyze the LiDAR results by microsimulation in AIMSUN. The research first introduces the concept of LiDAR-equipped signalized intersections and their potential to enhance traffic control precision. Two LiDAR sensors are strategically placed at the intersection of Marlboro Pike and Brooks Dr. in Coral Hills, MD, USA to capture real-time data on vehicle and pedestrian movements. The data are then processed to generate accurate and dynamic traffic profiles, ensuring the responsiveness of the green time allocation system to varying traffic conditions. The heart of this study lies in the integration of AIMSUN microsimulation with LiDAR data. Through meticulous modeling and simulation, the research explores the optimal green allocation at morning, mid-day, and afternoon peak hours' scenarios to comprehensively assess the impact of LiDAR-enabled dynamic signal control. The findings demonstrate that smart green time allocation, informed by real-time LiDAR data and implemented through AIMSUN microsimulation, significantly enhances intersection efficiency. By adapting signal timings to real-time traffic demands, congestion, travel times, and emissions are reduced. Furthermore, this research highlighted that the optimal green time allocation in morning, mid-day, and afternoon peak hour intervals can improve the delay time by 55.3%, 59.7%, and 55.6%, respectively. In conclusion, this paper sheds light on the potential of LiDAR technology to transform intersection management. Through a case study involving two LiDAR sensors and AIMSUN microsimulation, it reveals the tangible benefits of dynamic signal control in enhancing intersection efficiency and creating more sustainable urban environments. These findings are pivotal in advancing the discourse on modern urban traffic management and promoting data-driven solutions for the challenges of today's cities.

Keywords: LiDAR sensor; signalized intersections; green time allocation; delay time; microsimulation; AIMSUN software

1. Introduction

The challenge of managing urban mobility becomes more difficult as cities grow. Signalized intersections play a crucial role in ensuring the smooth operation of cities [1–4]. These intersections serve as critical nodes in the transportation network, orchestrating the flow of vehicles, pedestrians, and cyclists. The efficacy of traffic control at these junctions is essential for mitigating congestion, reducing emissions, and ensuring the safety of all road users [1,4–6]. In pursuit of enhanced intersection efficiency, recent years have witnessed the emergence of smart and data-driven traffic management systems. Among these innovations, LiDAR (Light Detection and Ranging) technology has shown great promise in revolutionizing the precision and adaptability of signalized intersection control. LiDAR sensors, with their ability to capture detailed, real-time data about the movement and behavior of vehicles and pedestrians, offer an opportunity to advance traffic management to a new level of sophistication [1–4,6–8,11,13].

This study focuses on a signalized intersection in MD, USA that equipped with two LiDAR sensors. In order to investigate the advantages of LiDAR sensor technology in signalized intersections, a practical study was conducted to explore the synergistic potential of LiDAR and microsimulation in optimizing the allocation of green time at signalized intersections. Smart green time allocation, tailored to the real-time traffic dynamics, can bring substantial improvements in intersection throughput, reduced delays, and lowered environmental impact [1]. Two LiDAR sensors continuously monitored the traffic flow at different intersection's approaches. This data is then processed and analyzed to create dynamic traffic profiles, enabling the traffic signal controller to make informed decisions about green time allocation. The integration of LiDAR data with AIMSUN microsimulation provides a robust framework for assessing the impact of this technology on intersection efficiency under diverse traffic conditions.

The research presents the impacts of dynamic green time allocation on traffic performance, safety, and environmental sustainability. Furthermore, the implications of these findings for urban planners, traffic engineers, and policymakers were explored aiming to address the ever-growing challenges of urban mobility. In essence, this study underscores the potential of LiDAR technology to usher in a new era of smart, data-driven traffic management, and the pivotal role it can play in enhancing intersection efficiency to meet the demands of urbanization and create sustainable urban environments.

2. Data Analysis

As the case study, the intersection of Marlboro Pike - Brooks Dr. in Coral Hills, MD, USA was selected. This intersection is located in Prince George's County of Maryland state and it is surrounded by various commercial land-uses. In order to understand intersection signal timing conditions, LiDAR data from October 1st to 15th, 2023 was analyzed. **Figure 1** shows the location of the intersection and the main land uses surrounding it. LiDAR sensors are depicted by two red circles.



Figure 1. Marlboro Pike & Brooks Dr. intersection [1].

During the specified time interval (the first two weeks of October 2023), the volume of vehicles, pedestrians, and bicyclists was analyzed. Southbound of the intersection has three lanes (one for SBR, one for SBT, and one for SBL). The research focuses on the phase #6 of the traffic signal that controls South Bound Straight Thru (SBT), and South Bound Left Turn (SBL). Due to the high frequency of yellow and red light runners, as well as conflict between V2V and V2P, this phase was selected. In order to minimize vehicle delays and congestion at the intersection, this study attempts to determine the optimal green allocation based on these two crucial movements. **Table 1** illustrates the vehicle counts (total of NS and NE movements) from October 1st to 15th.

Table 1. Hourly Vehicle Volume Collected by the LiDAR Sensor.

Hourly Time Interval	1-Oct	2-Oct	3-Oct	4-Oct	5-Oct	6-Oct	7-Oct	8-Oct	9-Oct	10-Oct	11-Oct	12-Oct	13-Oct	14-Oct	15-Oct
00:00 - 01:00 AM	123	68	55	58	66	95	93	100	63	64	68	52	75	103	68
01:00 - 02:00 AM	114	42	34	31	37	55	80	55	54	35	40	27	48	52	68
02:00 - 03:00 AM	58	24	27	20	37	37	48	35	37	25	34	18	25	46	26
03:00 - 04:00 AM	49	31	29	39	32	41	44	37	15	19	25	20	29	47	21
04:00 - 05:00 AM	43	35	51	35	30	45	23	36	28	32	33	42	45	48	22
05:00 - 06:00 AM	32	78	70	74	74	84	41	35	47	75	71	63	79	63	49
06:00 - 07:00 AM	60	93	105	110	112	104	78	54	90	95	113	93	104	50	49
07:00 - 08:00 AM	106	219	222	218	218	187	145	106	125	228	224	205	182	129	86
08:00 - 09:00 AM	222	272	261	281	302	300	207	192	205	314	307	331	306	220	181
09:00 - 10:00 AM	283	287	257	264	319	328	273	292	275	287	304	319	349	276	281
10:00 - 11:00 AM	377	357	291	295	309	404	262	320	321	259	333	367	385	304	292
11:00 - 12:00 AM	396	343	352	379	416	408	337	332	349	328	387	300	386	351	363
12:00 - 13:00 PM	527	395	358	357	354	454	481	475	446	350	396	405	461	309	449
13:00 - 14:00 PM	525	412	328	446	376	393	497	502	394	408	409	395	358	325	460
14:00 - 15:00 PM	452	466	416	446	493	432	411	464	466	465	376	425	490	397	437
15:00 - 16:00 PM	414	426	504	448	524	564	392	375	464	451	543	435	498	336	396
16:00 - 17:00 PM	393	565	561	598	572	568	462	447	437	589	617	564	542	413	396
17:00 - 18:00 PM	424	633	608	606	646	566	500	343	460	627	603	629	595	377	352
18:00 - 19:00 PM	326	494	626	627	582	439	476	326	432	481	539	572	502	297	334

19:00 - 20:00 PM	343	367	421	390	336	355	381	251	317	366	363	408	461	283	304
20:00 - 21:00 PM	248	225	307	338	308	334	266	223	266	269	281	289	356	193	248
21:00 - 22:00 PM	178	187	211	228	173	280	200	143	174	153	178	220	271	132	123
22:00 - 23:00 PM	126	130	128	145	150	227	186	106	129	121	156	176	230	161	125
23:00 - 24:00 PM	89	100	112	104	108	162	145	94	70	91	103	103	162	139	90
ADT*	246	260	264	272	274	286	251	223	236	256	271	269	289	210	218

*Average Daily Traffic (ADT).

Between October 1st and 15th, the number of pedestrians passing from the southbound direction is shown in **Table 2**.

Table 2. Hourly Pedestrian Volume Collected by the LiDAR Sensor.

Hourly Time Interval	1- Oct	2- Oct	3- Oct	4- Oct	5- Oct	6- Oct	7- Oct	8- Oct	9- Oct	10- Oct	11- Oct	12- Oct	13- Oct	14- Oct	15- Oct
00:00 - 01:00 AM	1	1	0	2	0	0	2	3	1	1	0	3	0	0	0
01:00 - 02:00 AM	0	1	0	1	0	1	2	0	1	0	0	0	0	0	1
02:00 - 03:00 AM	0	0	0	0	1	0	0	0	2	1	1	0	0	0	0
03:00 - 04:00 AM	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0
04:00 - 05:00 AM	0	1	1	0	2	3	1	0	3	3	3	1	1	0	0
05:00 - 06:00 AM	1	2	2	2	0	1	0	0	1	0	0	2	2	0	0
06:00 - 07:00 AM	0	4	0	4	4	4	1	1	2	3	5	3	2	0	0
07:00 - 08:00 AM	0	7	5	3	3	2	0	2	0	4	7	5	2	1	4
08:00 - 09:00 AM	3	11	11	7	4	7	5	2	2	10	7	5	4	2	0
09:00 - 10:00 AM	8	9	6	7	3	2	1	4	5	7	4	7	6	1	6

10:00 - 11:00 AM	4	10	0	4	5	8	4	5	3	6	4	3	10	2	6	
11:00 - 12:00 AM	5	5	8	3	6	1	5	4	5	7	8	2	9	3	4	
12:00 - 13:00 PM	6	9	8	2	6	10	10	4	8	6	4	4	3	2	8	
13:00 - 14:00 PM	4	12	1	4	3	5	6	11	8	9	2	4	3	5	5	
14:00 - 15:00 PM	11	10	6	5	6	9	7	5	12	0	3	6	10	3	6	
15:00 - 16:00 PM	5	9	9	13	10	5	8	10	11	8	2	4	5	1	3	
16:00 - 17:00 PM	4	8	5	9	5	5	11	3	7	5	9	5	8	6	3	
17:00 - 18:00 PM	13	8	13	5	8	13	4	6	13	7	7	8	1	7	5	
18:00 - 19:00 PM	14	7	4	9	17	7	4	8	5	8	9	14	7	1	9	
19:00 - 20:00 PM	8	10	8	7	9	7	9	2	6	7	9	1	9	6	12	
20:00 - 21:00 PM	3	4	9	6	3	9	6	6	1	3	6	5	4	4	2	
21:00 - 22:00 PM	0	1	3	4	8	5	7	0	11	3	0	11	6	2	2	
22:00 - 23:00 PM	5	0	0	2	0	3	6	0	8	2	4	5	12	5	0	
23:00 - 24:00 PM	2	0	2	7	1	3	1	3	3	0	3	1	4	0	0	
ADT	4	5	4	5	4	5	4	3	5	4	4	4	4	5	2	3

Between October 1st and 15th, **Table 3** shows the number of bicyclists passing from the southbound direction hourly.

Table 3. Hourly Bicyclist Volume Collected by the LiDAR Sensor.

Hourly Time Interval	1- Oct	2- Oct	3- Oct	4- Oct	5- Oct	6- Oct	7- Oct	8- Oct	9- Oct	10- Oct	11- Oct	12- Oct	13- Oct	14- Oct	15- Oct
00:00 - 01:00 AM	0	0	0	0	4	3	0	0	0	0	0	0	0	0	0
01:00 - 02:00 AM	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0

02:00 - 03:00 AM	5	1	0	0	0	0	1	0	0	0	0	0	0	0	0
03:00 - 04:00 AM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
04:00 - 05:00 AM	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0
05:00 - 06:00 AM	0	1	0	0	1	0	0	0	1	0	0	0	0	1	0
06:00 - 07:00 AM	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
07:00 - 08:00 AM	0	0	1	0	1	0	0	0	0	0	0	2	1	0	0
08:00 - 09:00 AM	0	0	2	1	1	0	0	0	1	0	0	0	0	0	1
09:00 - 10:00 AM	1	1	0	4	2	1	0	0	0	1	0	0	2	0	0
10:00 - 11:00 AM	0	0	1	1	2	2	0	1	1	1	1	0	2	0	0
11:00 - 12:00 AM	1	1	1	1	0	0	1	0	0	1	1	0	3	1	1
12:00 - 13:00 PM	0	0	0	0	0	0	1	0	1	0	0	1	1	1	0
13:00 - 14:00 PM	2	0	0	1	0	0	0	1	0	1	2	0	1	0	1
14:00 - 15:00 PM	0	0	0	1	0	0	0	1	0	0	4	1	1	1	1
15:00 - 16:00 PM	0	1	1	2	1	2	3	1	1	1	2	0	1	4	0
16:00 - 17:00 PM	2	1	0	1	0	1	0	3	2	1	0	2	1	0	0
17:00 - 18:00 PM	2	2	1	3	2	0	3	0	2	0	1	5	2	0	2
18:00 - 19:00 PM	0	2	2	0	2	1	4	0	0	0	0	1	0	0	0
19:00 - 20:00 PM	2	0	1	1	0	3	3	2	1	2	0	0	0	0	0
20:00 - 21:00 PM	1	0	10	2	2	1	0	2	1	2	0	1	4	0	1
21:00 - 22:00 PM	1	0	3	2	1	0	0	0	3	1	0	0	1	0	0

22:00 - 23:00	2	0	0	0	0	1	0	1	0	0	0	0	2	0	0
PM															
23:00 - 24:00	0	0	1	0	2	0	4	0	0	0	0	2	0	0	0
PM															
ADT	1	0	1	1	1	1	1	1	1	1	0	1	1	0	0

Figure 2 shows the changes in speed at the intersection's different approaches.

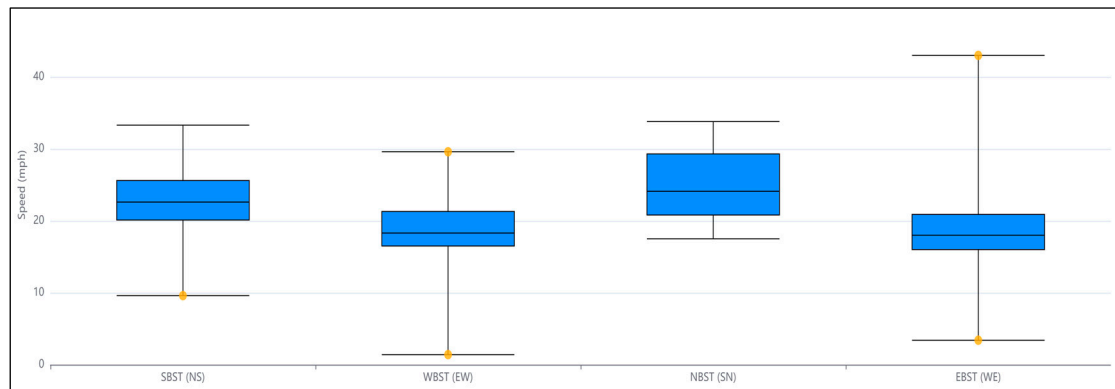


Figure 2. Speed Changes In Different Intersection's Approaches - From October 1st to 15th.

LiDAR sensors collect 22.6 mile/h, 18.3 mile/h, 24.1 mile/h, and 18 mile/h as the average speeds for NS (SBT), EW (WBT), SN (NBT), and WE (EBT) movements. According to the speed diagram (**Figure 2**), north-south approaches to the intersection have higher diurnal speeds.

3. Smart Green Time Allocation

Smart Green Time Allocation (SGTA) is a dynamic traffic signal control strategy that adapts green time allocations in response to real-time traffic conditions. SGTA relies on data from various sensors, including LiDAR, to make informed decisions and optimize signal timings for improved traffic flow. Traditional signal control strategies often rely on fixed-time plans, which are not adaptive to fluctuating traffic conditions [9,10,12]. The advantages of implementing SGTA at a signalized intersection equipped with LiDAR sensors are multi-fold including:

- 1) Improved Traffic Flow: SGTA dynamically adjusts green time allocations, ensuring that traffic moves smoothly, reducing delays, and optimizing vehicle progression through the intersection.
- 2) Reduced Congestion: Queue lengths during peak hours are significantly reduced as SGTA efficiently manages signal timings, reducing stop-and-go traffic patterns and associated congestion.
- 3) Enhanced Safety: SGTA reduces the likelihood of crashes and conflicts at the intersection by optimizing signal timings and reducing the chances of rear-end collisions.
- 4) Environmental Impact: By minimizing congestion and keeping traffic moving efficiently, SGTA leads to reduced fuel consumption, emissions, and improved air quality.

SGTA relies on processed LiDAR data to make real-time decisions about signal timing. The system assesses the current traffic conditions, identifying congestion, queues, and traffic patterns. Based on this assessment, SGTA dynamically adjusts green time allocations for different phases of the intersection, optimizing traffic flow. SGTA interacts with the traffic signal control system to implement the adjusted green time allocations. This integration ensures that the signals respond promptly to the changing traffic conditions, allowing for smoother traffic flow and reduced congestion. The advantages of SGTA with LiDAR sensors are numerous. It offers dynamic and real-

time signal control, reducing delays and improving traffic flow. It also minimizes congestion and lowers the likelihood of traffic crashes. However, challenges such as data processing complexities, sensor maintenance, and cost considerations should not be overlooked. Considering the previous author's study [1], and after monitoring the intersection's southbound movements accurately from October 1st to 15th, the hourly GTA (green time allocation) was identified for phase #6. The optimal green time allocation for phase #6 can be seen in **Table 4**.

Table 4. Optimal Green Time Allocation (sec) for Phase #6.

Hourly Time	1-Oct	2-Oct	3-Oct	4-Oct	5-Oct	6-Oct	7-Oct	8-Oct	9-Oct	10-Oct	11-Oct	12-Oct	13-Oct	14-Oct	15-Oct
00:00 - 01:00 AM	34.5	31.3	32.6	32.5	32.6	31.9	33.0	34.3	33.1	32.9	34.3	32.6	32.1	32.3	31.3
01:00 - 02:00 AM	32.7	27.8	29.5	26.2	28.5	29.6	30.6	32.8	31.8	28.2	28.3	32.1	27.9	31.6	32.3
02:00 - 03:00 AM	31.0	24.2	23.7	23.9	26.1	24.4	29.6	31.1	26.2	23.3	23.2	24.3	24.5	29.0	30.7
03:00 - 04:00 AM	28.9	22.6	23.2	22.9	22.6	23.1	27.5	28.9	25.6	22.5	22.9	22.5	23.8	28.8	28.1
04:00 - 05:00 AM	26.6	24.1	23.5	24.8	25.0	24.8	27.4	31.3	25.8	24.1	24.3	24.4	24.2	27.2	25.7
05:00 - 06:00 AM	24.9	25.4	24.6	25.4	25.6	25.7	27.1	25.4	26.1	24.6	25.4	23.4	25.8	27.2	25.8
06:00 - 07:00 AM	24.9	25.7	25.6	28.4	26.3	27.4	27.9	25.8	25.7	26.1	26.9	26.5	25.6	25.9	26.7
07:00 - 08:00 AM	26.5	25.5	27.0	25.7	29.5	26.9	28.0	27.2	26.2	26.2	26.5	27.0	26.4	27.3	27.0
08:00 - 09:00 AM	28.4	26.6	25.5	25.3	27.2	28.1	27.3	28.1	26.3	27.3	26.4	26.1	26.6	27.4	26.9
09:00 - 10:00 AM	28.2	26.6	25.9	25.7	26.5	26.0	26.9	27.4	25.5	28.3	26.1	26.6	25.9	26.9	27.5
10:00 - 11:00 AM	27.8	26.8	28.1	28.2	27.7	27.0	27.7	28.3	26.5	26.9	26.6	27.7	27.8	27.0	26.0
11:00 - 12:00 AM	26.5	28.3	28.6	27.4	28.9	27.8	27.2	27.2	27.6	26.7	27.8	27.1	29.4	26.3	26.1
12:00 - 13:00 PM	27.6	29.1	29.4	29.8	30.5	28.9	27.5	26.6	27.4	28.9	29.0	29.1	29.9	26.9	26.4
13:00 - 14:00 PM	27.1	29.9	29.9	30.5	30.4	29.2	27.4	26.6	27.1	30.5	29.2	29.3	28.9	26.2	25.8
14:00 - 15:00 PM	24.7	27.5	29.2	29.6	28.6	28.3	27.4	26.6	26.2	28.2	27.3	29.9	30.4	26.3	26.0
15:00 - 16:00 PM	26.1	26.0	26.6	25.6	26.5	26.8	26.1	24.5	27.1	25.8	26.2	26.7	27.2	27.3	27.4

16:00 - 17:00 PM	25.6	25.6	26.0	25.6	27.1	25.2	25.7	26.2	25.5	25.8	25.8	26.0	25.3	25.6	26.0
17:00 - 18:00 PM	25.7	24.9	24.9	26.2	25.5	24.6	24.6	26.3	27.3	25.5	21.4	24.7	26.1	24.7	26.2
18:00 - 19:00 PM	26.8	28.3	27.4	26.2	26.7	25.2	26.0	27.3	28.1	26.7	26.0	25.9	26.2	26.7	27.9
19:00 - 20:00 PM	29.6	29.4	28.2	27.9	27.4	26.6	27.6	29.1	30.2	28.7	30.7	29.0	26.7	31.6	29.4
20:00 - 21:00 PM	31.7	32.4	31.7	31.5	30.6	28.2	30.4	29.0	30.6	33.0	31.8	30.3	29.3	28.3	31.2
21:00 - 22:00 PM	33.6	34.3	33.4	33.5	32.2	31.7	31.5	33.9	32.7	34.0	32.2	33.3	31.6	32.4	33.5
22:00 - 23:00 PM	34.1	33.4	33.7	34.1	33.4	31.3	31.5	34.0	34.7	33.7	34.3	34.6	31.7	30.2	35.1
23:00 - 24:00 PM	35.1	34.8	34.2	34.5	34.1	32.6	33.4	34.9	35.2	34.9	35.9	34.4	32.6	33.1	34.0
Daily Average Green Time	28.7	27.9	28.0	28.0	28.3	27.5	28.3	28.9	28.3	28.0	27.8	28.1	27.7	28.2	28.5

As shown in **Table 4**, the optimal GTA was determined based on the total number of cycles per hour, and the average optimal GTA was calculated for all cycles. Basically, green time allocation at signalized intersections involves a dynamic allocation of time to different traffic movements (e.g., northbound, eastbound, left turns, through movements) during a signal cycle. The specific equations used for green time allocation can vary depending on the control strategy and software used. Green time allocation equations might also include constraints, such as minimum and maximum green time limits for each movement, coordination with adjacent intersections, and phase sequence constraints [14–16]. The specific mathematical model used for green time allocation can vary widely, and more advanced traffic signal control systems often utilize complex optimization algorithms, including linear programming, genetic algorithms, and simulation-based optimization.

It is important to note that while these are simplified representations of the equations involved in green time allocation, real-world traffic signal control systems can be highly complex and use advanced algorithms to optimize signal timing based on real-time data and specific objectives [16,17]. These systems often use proprietary equations and are developed based on the specific intersection requirements and control strategy. In order to assign optimal green time allocation to signalized intersections, the following equations are presented.

1. Traffic Flow and Demand (Q):

Q_{ij} : Traffic demand for movement i at phase j . This can be estimated as the number of vehicles per unit of time (e.g., vehicles per hour).

2. Cycle Length (C):

C : The total duration of a signal cycle in seconds. There is usually a fixed value for this, but it can be adjusted.

3. Green Time Allocation (GT_{ij}):

GT_{ij} : The green time allocated to movement i at phase j during one cycle.

4. Percentage Split (PS_{ij}):

PS_{ij}: The percentage of green time allocated to movement *i* at phase *j* relative to the total green time during the cycle. It is calculated as shown in **Equation (1)**:

$$PS_{ij} = (GT_{ij} / C) * 100\% \quad (1)$$

5. Optimization Objectives:

The specific equations for green time allocation can vary depending on the optimization objectives. Common objectives include:

a. Maximizing Throughput (Capacity): Maximize the number of vehicles that can pass through the intersection during the cycle. This can be expressed as shown in **Equation (2)**:

$$\text{Maximize: } \Sigma(Q_{ij} * GT_{ij}) \quad (2)$$

b. Minimizing Delay: Minimize the total delay experienced by vehicles at the intersection. In delay equations, the number of vehicles in the queue and the time they spend waiting can be taken into account as shown in **Equation (3)**:

$$\text{Minimize: } \Sigma(QL_{ij} * L_{ij}) \quad (3)$$

Where:

QL_{ij}: Queue length for movement *i* at phase *j*

L_{ij}: Average vehicle length

c. Minimizing Stops: Minimize the number of vehicle stops at the intersection. The equation could include the number of stops for each movement as can be seen in **Equation (4)**:

$$\text{Minimize: } \Sigma(\text{Stops}_{ij}) \quad (4)$$

Where:

Stops_{ij}: Number of stops for movement *i* at phase *j*

d. Minimizing Environmental Impact: Minimize emissions and fuel consumption, which can be related to the delay and queue length for each movement as can be seen in **Equation (5)**.

$$\text{Minimize: } \Sigma(\text{Emissions}_{ij}) \quad (5)$$

Where:

Emissions_{ij}: Emissions associated with movement *i* at phase *j*

4. Data Analysis Results

To investigate the optimal green time allocation from LiDAR sensors at the intersection of Marlboro Pike and Brooks Dr. in Coral Hills, MD, USA (**Table 4**), traffic volumes were determined on the peak day. In other words, the peak day from October 1st to 15th was specified, and the morning, mid-day, and afternoon hours of the peak day was selected to simulate in AIMSUN software. Considering the vehicle volume (count) collected by two LiDAR sensors, Friday, October 13th, 2023 was determined as the peak day. The passenger cars, trucks, and buses volumes (counts) were analyzed on October 13th and 07:30 – 08:30 AM, 13:45 – 14:45 PM, and 17:15 – 18:15 PM were specified as morning, mid-day, and afternoon peak hours. **Figures 3–5** demonstrate the hourly total volumes in October 13th.

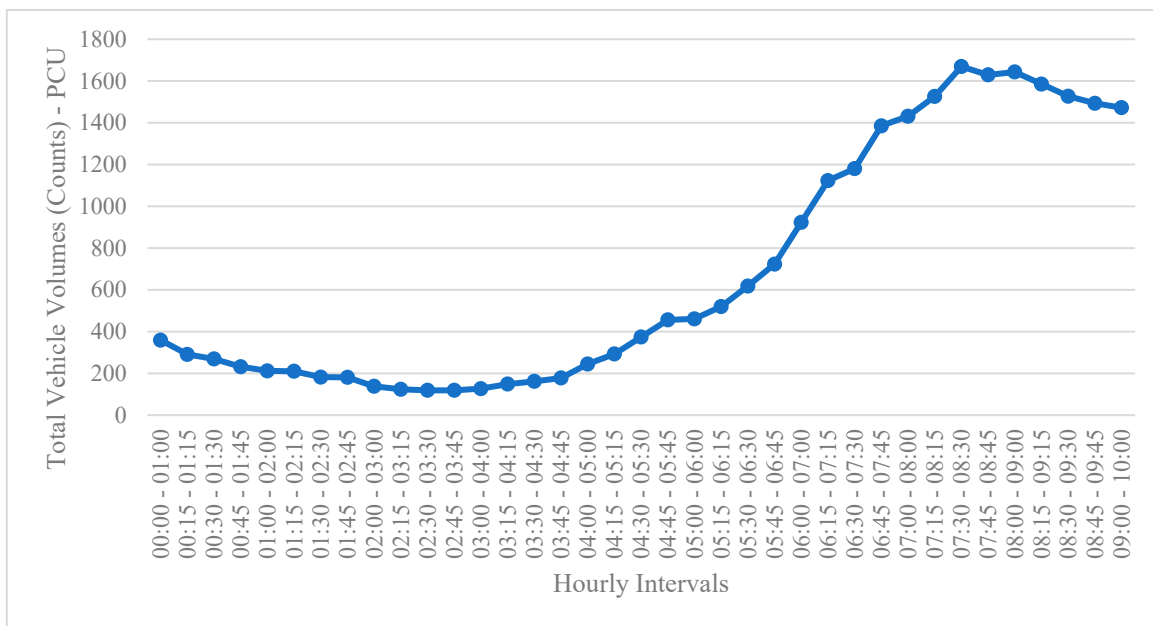


Figure 3. Vehicle Volumes (Counts) In the Morning Intervals on Friday, October 13th.

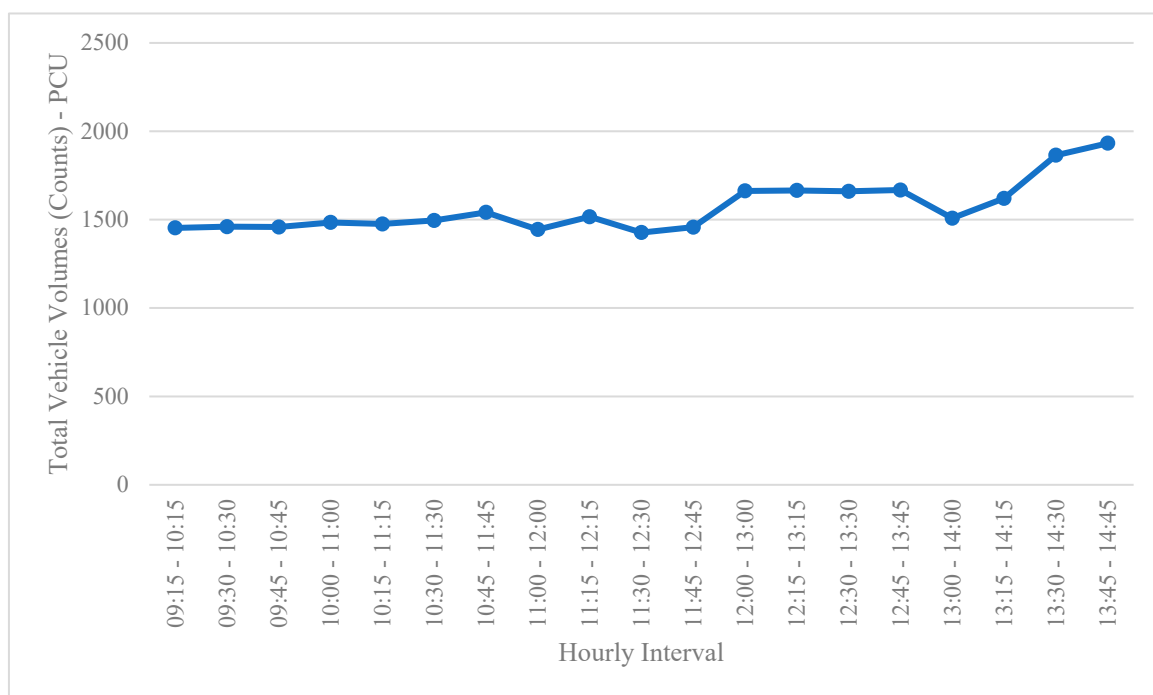


Figure 4. Vehicle Volumes (Counts) In the Mid-day Intervals on Friday, October 13th.

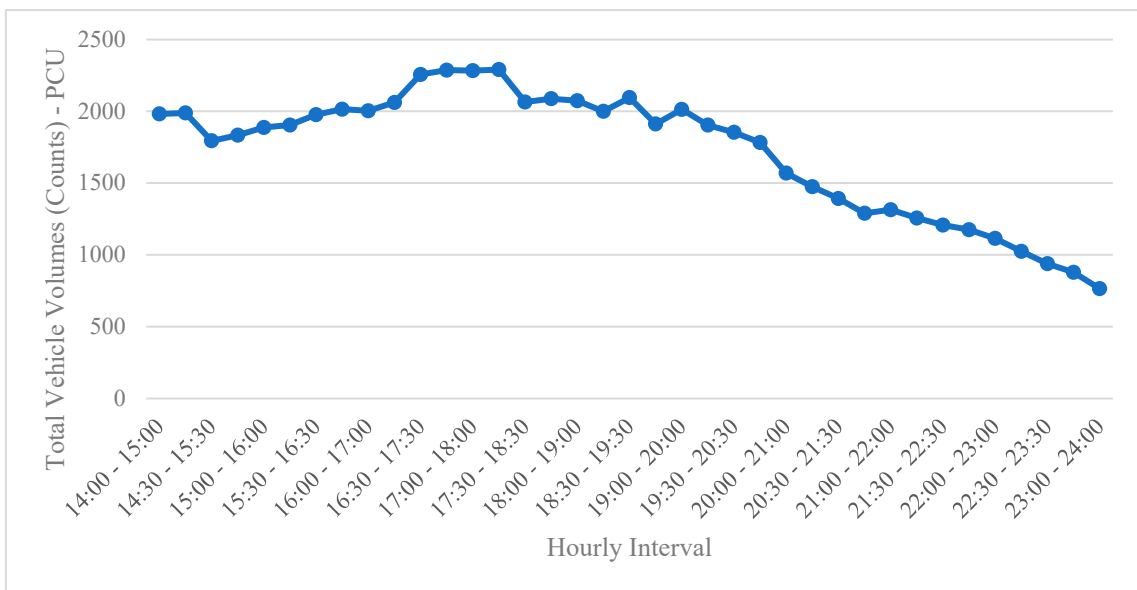


Figure 5. Vehicle Volumes (Counts) In the Afternoon and Mid-night Intervals on Friday, October 13th.

Figures 6–8 show the peak hour traffic volumes (counts) of each movement at the intersection.

				Marlboro Pike											
				Out	In		Total								
				778	465		1243								
				193	261	7	4								
				Right	Thru	Left	Peds								
				↓	↓	↓									
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				10/13/2023 - 07:30 - 08:30 AM											
				Vehicles and Pedestrian											
Brooks Dr	Total	903	309	Left	↑	Right	↓	23	32	Out	Brooks Dr				
	In	479	11	Thru	→	Thru	←	37	80	In					
	Out	424	3	Right	↓	Left	↑	18	2	Total					
				Left	Thru	Right	Peds	194	446	14	2				
				435	656		1091								
				Out	In		Total								
				Marlboro Pike											

Figure 6. Morning Peak Hour Volumes (07:30 - 08:30 AM).

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Figure 7. Mid-day Peak Hour Volumes (13:45 - 14:45 PM).

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Figure 8. Afternoon Peak Hour Volumes (17:15 - 18:15 PM).

Given that the LiDAR’s optimal green time allocation values of phase #6 in morning peak hour (07:30 – 08:30 AM – 29.3 sec), mid-day peak hour (13:45 – 14:45 PM – 29.7 sec), and afternoon peak hour (17:15 – 18:15 PM – 28.7 sec), the intersection was simulated in AIMSUN software. Calibrating a simulated signalized intersection within traffic simulation software is a critical step to ensure that the simulated scenario accurately reflects real-world conditions. In this research, the calibration process of the simulated signalized intersection was performed using the AIMSUN software, focusing on the intricate steps and methodologies involved. The calibration process involves an iterative approach that refines the simulation model to yield results that align closely with observed

traffic behaviors. AIMSUN, with its advanced features and capabilities, provides a robust platform for this undertaking.

The calibration process typically begins with the collection of real-world data at the target intersection, including traffic counts, vehicle speeds, queue lengths, and signal timings [8,18]. These empirical data serve as the baseline against which the simulation model will be calibrated. In AIMSUN, model parameters such as driver behavior, vehicle characteristics, and lane-specific details are adjusted to reproduce observed traffic patterns accurately. Through an iterative process of comparing simulation outputs with real-world data, adjustments are made to the model parameters until a satisfactory level of alignment is achieved. The successful calibration of a simulated signalized intersection in AIMSUN allows for the testing and evaluation of various traffic control strategies and infrastructure changes without the need for costly and time-consuming real-world experiments. The following steps were followed to simulate Marlboro Pike & Brooks Dr. signalized intersection in AIMSUN.

1. **Data Collection:** Begin by gathering comprehensive and accurate real-world traffic data at the target signalized intersection. This data should include information such as traffic counts, vehicle speeds, queue lengths, and signal timings. The quality and representativeness of the data are essential for calibration.

2. **Model Initialization:** Set up the simulation model in AIMSUN, including the road network, signal timings, and initial parameters. Ensure that the model reflects the physical characteristics of the actual intersection that incorporated data such as road geometry and lane configurations.

3. **Initial Simulation:** Conduct an initial simulation run using the uncalibrated model. This run will serve as a baseline to identify discrepancies between the simulation and real-world data.

4. **Parameter Adjustment:** Identify specific model parameters that may need adjustment to improve the model's accuracy. These parameters include driver behavior, vehicle characteristics, lane-specific attributes, or signal control settings.

5. **Iterative Process:** Calibration is an iterative process. Each iteration should aim to reduce the disparities between the model and real-world conditions.

6. **Sensitivity Analysis:** Perform sensitivity analyses to assess the impact of different parameter adjustments on the simulation outputs. This can help to understand which parameters have the most significant influence on the model's performance.

7. **Validation and Validation Data:** Reserve a portion of the collected data for validation purposes. It is recommended that this information not be used during the calibration process, but instead be used to assess the accuracy of the calibrated model independently. This separation helps ensure that the model does not become overfit to the calibration data.

8. **Documentation:** Thoroughly document all parameter adjustments, iterations, and results throughout the calibration process. The number of iterations required to calibrate a simulated signalized intersection in AIMSUN can vary significantly depending on the complexity of the intersection, the quality of the available data, the accuracy of the initial model, and the specific calibration objectives. Calibration aims to minimize the discrepancies between the simulated results and real-world data. The iteration process should be continued until an acceptable level of accuracy and alignment with the observed traffic conditions is gained. Additionally, the complexity of the simulation model can affect the number of iterations. A more complex model, with multiple traffic movements, intricate lane configurations, and various signal phases, may require more iterations to accurately represent the real-world intersection. It is worth mentioning that there are no specific mathematical equations to determine the exact number of iterations needed to calibrate a simulated signalized intersection in AIMSUN. The number of iterations required is determined by a dynamic and data-driven process that depends on several factors and it is not a quantifiable variable that can be expressed mathematically. Instead, it is determined through experience, observation, and judgment during the calibration process. To provide an accurate simulation, 10 iterations were considered to simulate morning, mid-day, and afternoon peak hours [18].

9. Model Validation: After calibration, the model should be validated by comparing the simulation outputs with the reserved validation data. The model should demonstrate good performance in replicating real-world traffic conditions not used during calibration.

The network was simulated in AIMSUN software, and 29.3 sec, 29.7 sec, and 28.7 sec were considered as the optimal green time for phase #6 in morning, mid-day, and afternoon peak hours. **Figure 9** illustrates the simulated network in AIMSUN, and **Table 5** shows the traffic factors for morning peak hour (07:30 – 08:30 AM).

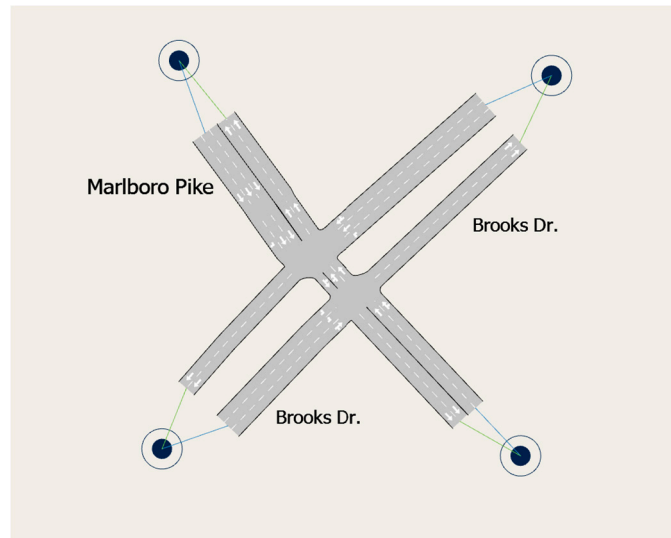


Figure 9. Simulated Network in AIMSUN.

Table 5. orning Peak Hour Traffic Values – AIMSUN Output.

Time Series	Value	Units
Delay Time	12.77	sec/mi
Density	7.55	veh/mi
Flow	1681.4	veh/h
IEM Emission - CO2	46420.1	g
IEM Emission - NOx	123.5	g
IEM Emission - PM	25.19	g
IEM Emission - VOC	24.96	g
Input Flow	1686.2	veh/h
Speed	30.23	mph
Stop Time	0.46	sec/mi
Total Distance Traveled	118.1	mi
Total Number of Stops	25.3	
Total Travel Time	4.02	h
Travel Time	122.74	sec/mi

Table 6 shows the traffic results for mid-day peak hour (13:45 – 14:45 PM).

Table 6. Mid-day Peak Hour Traffic Values - AIMSUN Output.

Time Series	Value	Units
Delay Time	13.82	sec/mi
Density	7.94	veh/mi
Flow	1893	veh/h
IEM Emission - CO2	49414.17	g
IEM Emission - NOx	136.45	g
IEM Emission - PM	27.09	g
IEM Emission - VOC	26.42	g
Input Flow	1939.3	veh/h
Speed	29.98	mph
Stop Time	0.53	sec/mi
Total Distance Traveled	127.09	mi
Total Number of Stops	38.8	
Total Travel Time	4.84	h
Travel Time	124.15	sec/mi

Table 7 shows the traffic results for afternoon peak hour (17:15 – 18:15 PM).

Table 7. Afternoon Peak Hour Traffic Values - AIMSUN Output.

Time Series	Value	Units
Delay Time	16.17	sec/mi
Density	7.55	veh/mi
Flow	2291.4	veh/h
IEM Emission - CO2	69515.63	g
IEM Emission - NOx	177.29	g
IEM Emission - PM	40.12	g
IEM Emission - VOC	34.79	g
Input Flow	2296.8	veh/h
Speed	29.52	mph
Stop Time	0.99	sec/mi
Total Distance Traveled	158.18	mi
Total Number of Stops	59.6	
Total Travel Time	5.54	h
Travel Time	126.39	sec/mi

Figure 10 compares the delay time results of the current signal timing under normal conditions with results obtained through microsimulation in AIMSUN by assigning the optimal green time. As can be seen in **Figure 10**, the optimal green time allocation for phase #6 in morning, mid-day, and afternoon peak hour intervals can improve the delay time of this phase by 55.3%, 59.7%, and 55.6%, respectively.

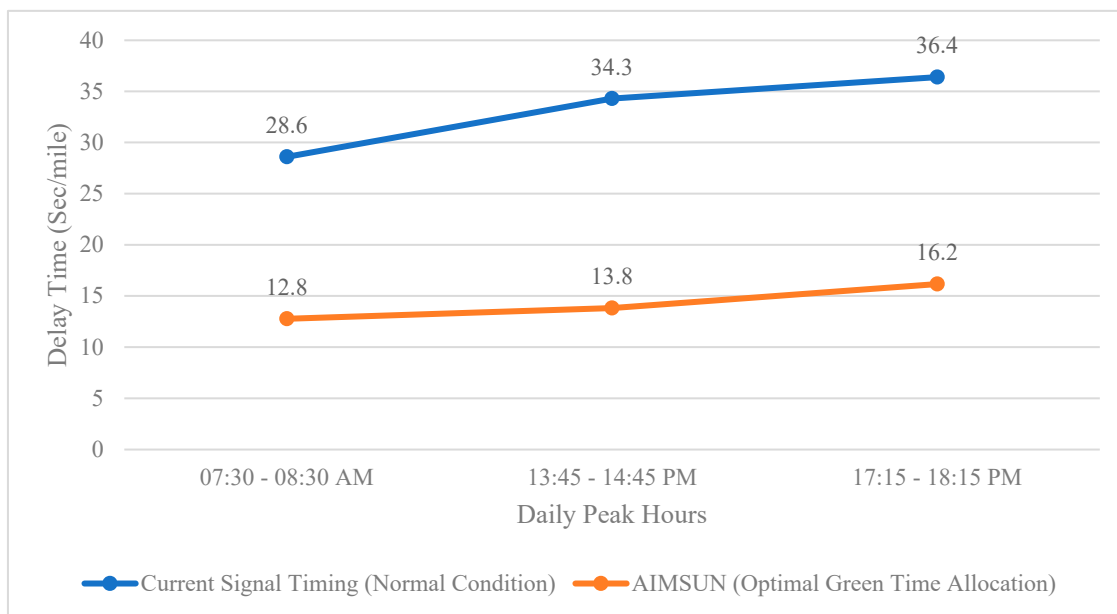


Figure 10. Comparison of Delay Time (Sec/Mile) between Normal Condition and Optimal Green Time Allocation.

5. Discussion & Conclusion

This research has delved into the extensive exploration of Smart Green Time Allocation (SGTA) at a signalized intersection, bolstered by the integration of two LiDAR sensors and the utilization of microsimulation in the AIMSUN software. The significance of this study lies in its demonstration of the pivotal role that SGTA, fortified with LiDAR technology, can play in revolutionizing traffic management and signalized intersection control in urban environments [19–22]. By harnessing real-time data provided by LiDAR sensors, SGTA proves to be a dynamic, adaptable, and responsive solution capable of mitigating traffic congestion, enhancing safety, and optimizing green time allocations.

The research findings have showcased the tangible advantages of SGTA over traditional, fixed-time signal control methods. Notably, the dynamic nature of SGTA, driven by real-time traffic conditions, ushers in an era of smarter traffic management. The efficiency of signalized intersections significantly benefits from this approach, with reduced delays, improved traffic flow, and a marked reduction in queue lengths, contributing to a more fluid and streamlined commuting experience for all road users.

Beyond its efficiency, SGTA's contributions extend to the realm of environmental sustainability and road safety. By minimizing congestion and enhancing vehicle progression, SGTA curtails emissions and fuels consumption, translating to a notable reduction in the environmental footprint of urban transportation. Furthermore, the safety benefits arising from SGTA's ability to reduce crashes and conflicts at signalized intersections cannot be understated. The technology's capacity to mitigate the risk of collisions underscores its potential to enhance road safety.

While acknowledging challenges in data processing, sensor maintenance, and cost considerations, the research underscores the transformative power of SGTA in signalized intersection control. The calibration process, a crucial aspect of this study, serves as a testament to the adaptability and efficiency of the AIMSUN software for microsimulation. Through this comprehensive examination, the research not only elucidates the advantages of SGTA but also serves as a practical study for future research, innovation, and implementation.

First and foremost, future studies could delve deeper into the intricacies of LiDAR technology and its evolving capabilities. As LiDAR sensors become more advanced and cost-effective, exploring their integration into various aspects of traffic management beyond signalized intersections could offer invaluable insights. LiDAR's role in data collection and traffic monitoring can extend to broader

transportation systems, urban planning, and even autonomous vehicle applications. Consequently, research can concentrate on optimizing LiDAR data processing algorithms and expanding its applicability in diverse traffic scenarios.

In terms of SGTA, there is room for advanced optimization techniques. Future studies can investigate more complex and adaptive algorithms that consider not only real-time traffic conditions but also predictive analytics. Machine learning and artificial intelligence models can be integrated to forecast traffic patterns, enabling even more proactive green time allocation adjustments. Furthermore, research could focus on SGTA's scalability and potential implementation at a network level, where multiple signalized intersections interact with each other, creating an intelligent and synchronized traffic management system.

The role of SGTA in promoting sustainability and reducing environmental impact is an area ripe for exploration. Future studies can delve into the quantifiable benefits of SGTA in terms of emissions reductions, energy efficiency, and the promotion of sustainable transportation modes. Additionally, the economic implications of adopting SGTA can be investigated, taking into account savings in fuel costs, reduced infrastructure wear and tear, and improved overall traffic efficiency.

Furthermore, as traffic management and urban mobility evolve, an increased focus on cybersecurity is warranted. With the integration of LiDAR sensors and advanced control systems, the vulnerability to cyber threats becomes a critical concern. Future studies should address the development of secure and resilient SGTA systems to safeguard against potential cyber-attacks and ensure the continued reliability of urban traffic management.

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