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Tam Denetimli Kavşaklarda Şerit Kapasitesinin İncelenmesi

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Öz

Bu çalışma, Mersin'deki tam denetimli sinyal kontrol sistemiyle yönetilen bir kavşakta şerit kapasitesine etki eden faktörler incelenmektedir. Kapasite yönetimi, trafik akışındaki gecikmeleri azaltarak ve trafik sıkışıklığını hafifleterek önemli avantajlar sağlar. Bu durum, emisyonların azaltılması ve kentsel hava kalitesinin iyileştirilmesi gibi çevresel sürdürülebilirlik hedeflerine katkıda bulunabilir. Çalışmada, kuyruk uzunluğu, ağır vasıtaların yüzdesi ve boşaltım oranı gibi faktörlerin şerit kapasitesi üzerindeki etkileri detaylı olarak incelenmiştir. Analiz için ağırlıklı en küçük kareler tekniği kullanılmıştır, bu da verilerin istatistiksel olarak değerlendirilmesine ve sonuçların doğrulanmasına olanak sağlamıştır. Çalışmanın temel bulguları şunlardır: Ağır vasıtaların varlığı şerit kapasitesini azaltır. Kuyruk uzunluğunun artması şerit kapasitesinin artmasını sağlar. Boşaltım oranının artmasıyla, şerit kapasitesinin artma eğilimi vardır. Bu bulgular, kentsel ulaşım stratejilerini geliştirmek isteyen karar vericilere önemli bilgiler sunmaktadır. Özellikle trafik yönetiminde ve sürdürülebilir ulaşım politikalarının oluşturulmasında, bu tür analizlerin ve sonuçların dikkate alınması büyük önem taşımaktadır.

Anahtar kelimeler: Şerit kapasitesi, Doygun akım oranı, Ağırlıklandırılmış en küçük kareler, Hekzagonal histogram, Kentsel trafik

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Examination of Lane Capacity at Fully Actuated Intersections

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Abstract

This study investigates factors influencing lane capacity at a fully actuated intersection in Mersin.This study examines the factors affecting lane capacity at an intersection in Mersin managed by a fully actuated signal control system. Capacity management provides significant advantages by reducing delays in traffic flow and alleviating traffic congestion. This can contribute to environmental sustainability goals such as reducing emissions and improving urban air quality. The study thoroughly investigates the impact of factors such as queue length, the percentage of heavy vehicles, and discharge flow rate on lane capacity. The Weighted Least Squares (WLS) technique was used for the analysis, allowing for the statistical evaluation of the data and verification of the results. The key findings of the study are as follows: The presence of heavy vehicles reduces lane capacity. An increase in queue length leads to an increase in lane capacity. There is a tendency for lane capacity to increase with a higher discharge flow rate. These findings provide important insights for decision-makers looking to develop urban transportation strategies. It is important to take such analyses and results into consideration, especially in traffic management and the creation of sustainable transportation policies.

Keywords: Lane capacity, Saturation flow rate, Weighted least squares, Hexagonal histogram, Urban traffic

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1. Introduction

Signalized intersections are a fundamental element of urban transportation, essential for creating livable cities, enhancing traffic safety, and improving service levels [1-3]. Well-designed signal control systems, which regulate traffic flow from various approaches, can reduce delays and increase capacity, thereby maximizing the efficiency of the transportation network [4-5].

Today, urban transportation widely utilizes many signal control systems. Fixed-time signal control systems manage intersections based on predetermined signal timings, assuming constant traffic flow throughout the day [6]. However, these signal plans need to be updated and optimized considering instant traffic demand; fixed plans account for approximately 5-10% of traffic congestion and delays [7]. In such cases, real-time signal control systems, which adjust signal timings based on real-time traffic flow, are more suitable. Examples include fully actuated and adaptive signal control systems, which are widely preferred by transportation engineers. Adaptive systems are effective over larger areas with optimization potential, while fully actuated systems are ideal for managing specific traffic demands at the local level. Both systems are designed to improve traffic flow and provide a more efficient journey for drivers.

This study focuses on capacity analysis of saturated cycles at intersections managed by fully actuated signal control systems. Fully actuated intersections dynamically adjust signal timings based on real-time traffic demands, distributing the total intersection capacity to approach lanes according to traffic demand. Consequently, the capacity of the approach lanes varies from cycle to cycle. This variability will be modeled as a parameter called "lane capacity" within the scope of this study.

Lane capacity refers to the variable capacity offered to an approach lane during the green time defined by the signal system. The study examines the impact of traffic composition and flow parameters on lane capacity. The aim is to provide a comprehensive model for traffic engineering by linking traffic flow and composition parameters. The model evaluates capacity management at intersections controlled by fully actuated signal systems, aiming to reduce congestion and delays, thereby decreasing emissions and improving air quality in urban areas. Effective capacity management not only enhances intersection performance but also supports sustainable traffic management goals. This study seeks to demonstrate how traffic management practices intersect with sustainability goals, contributing to the development of holistic urban transportation planning approaches that prioritize both efficiency and environmental responsibility.

The article is organized as follows: The second section presents the literature review. The third section covers the data collection process. The fourth section details the methodology. The fifth section provides the descriptive evaluation and model results. The last section offers conclusions and discussions.

2. Literature

To achieve the operational capacity of an urban transportation network, achieving a thorough examination of signalized intersections is essential [5]. Signalized intersections can cause delays in traffic flow, increased fuel consumption, and higher emissions [8]. Consequently, researchers have extensively evaluated the performance of these intersections. These studies have demonstrated that the saturation flow rate is a crucial concept in assessing the capacity of signalized intersections [9].

The saturation flow rate plays a vital role in geometric design, signal control, and level of service evaluations at signalized intersections [10]. Numerous studies have investigated the factors affecting the saturation flow rate. These factors include turning vehicles (left and right) [11], the slope of the approach lane [12], lane width and markings [13-14], vehicle composition [15], pedestrian and bicycle activity [16], and signal characteristics [17].

The concept of discharge flow rate represents another parameter closely linked to intersection capacity. Researchers have analyzed the effects of green time and queue lengths on the discharge flow rate [16, 18-19]. Stanić et al. [20] noted that the discharge flow rate of the first four vehicles in the queue is significantly lower compared to other vehicles in the queue. Similarly, Karabulut et al. [19] reported that the discharge flow rate increases by approximately 30% after the first four vehicles. This is attributed to the significant initial lost times experienced by the first four vehicles in the queue. Chaudhry and Ranjitkar [18] observed a decrease in the discharge flow rate for vehicles at the end of the queue, a result supported by other studies as well [11, 21]. Researchers further observed that the discharge flow rate decreases as green time increases [19, 22]. Khosla and Williams [23] reported a similar trend; however, the decrease in discharge flow rate was not found to be statistically significant after the sixtieth second of the green phase.

3. Data

This study used traffic flow data from a fully actuated signal-controlled urban intersection in Mersin (Figure 1), namely Mall Intersection. The roundabout has four approach lanes, each with three lanes varying in width from 3.0 to 3.6 meters and a slight gradient of 2%. The intersection experiences mixed traffic and limited pedestrian activity. Traffic video recordings of the approach lanes were obtained from the Mersin Metropolitan Municipality during the morning peak hours of 7:30-9:30 under prevailing weather conditions for analysis.

Figure 1. Locations of Mall intersection

4. Methodology

Figure 2 illustrates the methodology. Figure 2 visually represents the methodological process. Traffic flow videos were analyzed using MATLAB® to determine time headways between vehicles. HCM [24] recommends a minimum of eight vehicles in a standing queue to achieve saturation flow. Therefore, only green periods with at least eight vehicles in the queue were considered. As a result, the analysis included 178 green periods (125 for the west approach and 53 for the east approach) (see Table 1).

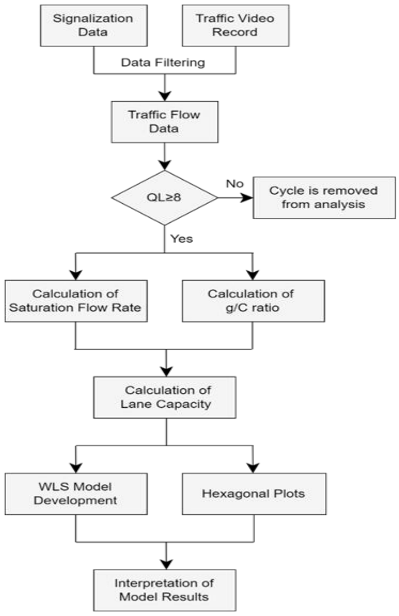

Figure 2. Flow chart of the proposed methodology

Table 1. Detail of West and East approach leg cycles

Approach Leg		West	East
Number of green periods		125	53
Green time (sec)	Min.	31	19
	Avg.	56	32
	Max.	72	35
Ratio of effective green time to cycle time	Min.	0.323	0.187
	Avg.	0.516	0.297
	Max.	0.673	0.366
Queue length (veh/cycle/lane)	Min.	8	8
	Max.	25	15
Departure volume (veh/cycle/lane)	Min.	9	8
	Max.	33	15
Discharge flow rate (veh/hour/lane)	Min.	1148	983
	Max.	1926	1815
Traffic composition (%)	PC	94.3	92.2
	HV	5.7	7.8

The capacity of signalized intersections depends on the saturated flow rate, effective green time, and cycle time. The lane capacity was calculated by Eq. 1 [24].

$$c_i = S_i.(g_i/C_i) \quad (1)$$

where c refers to the lane capacity (veh/hour/lane); S refers to the saturation flow rate; g refers to the effective green time (sec); C refers to the cycle time (sec). The saturation flow rate was calculated by Eq. 2 [24].

$$S_i = 1/h_{si} \quad (2)$$

where S_i refers to the saturation flow rate and h_{si} refers to the saturated headway (hour/veh). The saturated headway was calculated using Eq. 3 [24].

$$h_{si} = \left(\sum_{q=5}^{n} h_i\right)/(n-4) \quad (3)$$

where n is the total number of vehicles in a queue; and q is the time headway of q_{th} queued vehicle. Effective green time refers to the green time during which vehicles may proceed at saturation flow rate. The effective green time was calculated by Eq. 4 [24].

$$g_i = G_i + Y + AR - t_{Li} \quad (4)$$

where g_i refers to the effective green time (sec), G refers to the green time (sec), Y refers to the yellow time (sec), AR refers to the all-red time (sec) and t_L refers to the total lost time (sec).

The lane capacity expressed by Eq. 1 was calculated separately for each examined green period. Subsequently, the lane capacity was modeled using the Weighted Least Squares (WLS) method. Table 2 presents the details of the parameters used in the model.

Table 2. Details of parameters used in the lane capacity model

Variable Type	Variable	Notation	Unit
Dependent variable	Lane capacity	CAP	veh/hour/lane
Independent variables	Queue length	QL	veh/cycle/lane
	Percentage of heavy vehicles	HV	%
	Discharge flow rate	DFR	veh/hour/lane

The WLS model is a form of ordinary least squares (OLS) that assigns a weight to each observation by scaling the square of the residual. In OLS, observations are assumed to have constant variance, implying homoscedasticity. However, in many modeling scenarios, the homoscedasticity assumption is not valid. In such cases, the WLS modeling technique may be preferred. If the covariance structure of the data is known, Generalized Least Squares (GLS) can be used [25]. A special case of GLS is WLS, which assumes heteroscedasticity but uncorrelated residuals, meaning there are no cross-covariance terms. The general equation of the WLS model can be expressed as Eq. 5 [25]:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \quad (5)$$

where y is the dependent variable, x represents the independent variables, and β is the coefficient of the variables. WLS assigns different weights to each data point based on the variability of residuals associated with that data point. It accomplishes this by assigning larger weights to observations with smaller variances and smaller weights to observations with larger variances [25]. In WLS, each observation may have a different weight, denoted as w_i, where i represents each observation. The weighted sum of squared residuals is minimized as seen in Eq. 6 [25]:

$$minimize \sum_{i=1}^{n} w_i (y_i - \beta_0 - \beta_1 x_{1i} - \beta_2 x_{2i})^2 \quad (6)$$

where n is the number of observations. As a result, the impact of heteroscedasticity on model predictions is reduced by minimizing the weights at each data point. Therefore, in situations where heteroscedasticity is present, using WLS can improve model performance and provide more accurate predictions.

5. Results

The foundation of Ordinary Least Squares (OLS) analysis relies on the presupposition that the independent variables integrated into the model exhibit statistical independence. Therefore, assessing whether these variables adhere to this assumption requires conducting a Pearson correlation analysis. Figure 3 depicts the correlation coefficients among the independent variables, providing insight into their interrelationships. According to the criteria outlined by Hosseinzadeh [26], correlation coefficients exceeding an absolute value of 0.70 signify a substantial correlation between independent variables. The correlation matrix is depicted in Figure 3. QL, HV, and DFR are not highly correlated with each other (see Fig. 3). This implies that all independent variables can be used together.

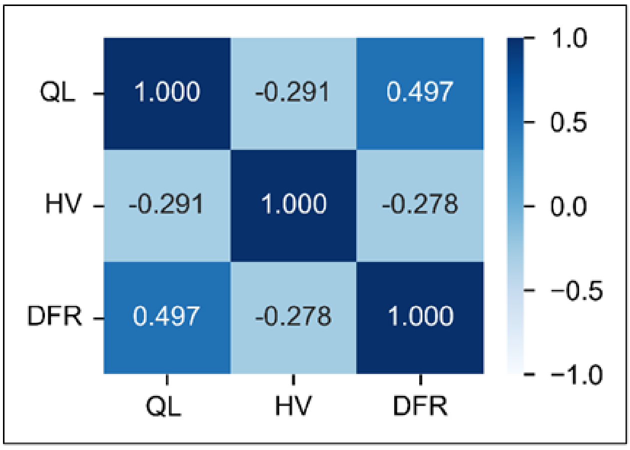

Figure 3. Correlation matrix of independent variables

Table 3 summarizes the results of the Weighted Least Squares (WLS) model. QL and DFR emerged as significant factors positively influencing CAP. On the other hand, HV emerged as a significant factor contributing adversely to CAP. All independent variables in the developed model were found to be statistically significant at the 5% significance level. Additionally, the adjusted R-squared value of this model is 0.927.

Table 3. Result of lane capacity model

Independent Variables	Coeff.	p-value	R^2
Queue length (QL)	25.906	0.000	
Percentages of heavy vehicles (HV)	-10.803	0.000	0.927
Discharge flow rate (DFR)	0.339	0.000	

Hexagonal histograms also visualize the relationship between the dependent and independent variables (see Fig. 4). These plots demonstrate the distribution and density differences between variables. If one variable depends on the other, denser colored areas with more observations will appear on the hexagonal histogram. Additionally, hexagonal histograms help in understanding the effect of the independent variable on the dependent variable and identifying clusters. The relationships observed between the dependent and independent variables in hexagonal histograms can be verified with statistical measurements such as the Pearson correlation coefficient.

Two distinct clusters are observed in the relationship between queue length and lane capacity, centered around queue lengths of 10 and 15 vehicles. The cluster around a queue length of 15 vehicles corresponds to a higher lane capacity (see Fig. 4). A single cluster is observed in the relationship between heavy vehicle percentage and lane capacity. Similarly, a single cluster is also observed in the relationship between discharge flow rate and lane capacity. This cluster indicates that lane capacity increases with an increasing discharge flow rate (see Fig. 4).

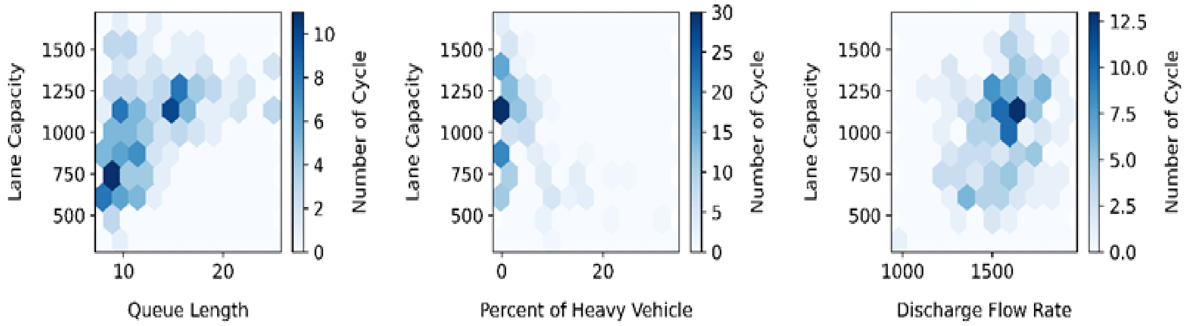

Figure 4. Hexagonal histogram of independent variables with lane capacity

6. Conclusion

This study examines the concept of variable capacity at intersections controlled by fully actuated signal systems. The aim is to determine the impact of factors such as queue length (QL), heavy vehicle percentage (HV), and discharge flow rate (DFR) on capacity at intersections where these systems are used.

Capacity management aims to reduce traffic congestion and delays, thereby decreasing emissions and improving urban air quality. This not only enhances intersection performance but also contributes to sustainable traffic management goals. The model developed in the study can guide decision-makers in sustainable urban transportation strategies and provides a significant tool for evaluating capacity management at intersections using fully actuated signal control systems. The results are summarized below:

- The adverse effect of heavy vehicles on road capacity is notable. These vehicles, being larger and slower, can negatively impact traffic flow and reduce lane capacity. An increasing percentage of heavy vehicles can affect the driving behavior of passenger car drivers, reducing discharge flow rate and average speed, leading to a decrease in lane capacity.
- An increase in queue length results in a significant increase in lane capacity. Long queues facilitate more efficient use of green time, enhancing saturation flow rates and thereby increasing lane capacity. Conversely, short queues can lead to inefficient use of green time, reducing capacity. Therefore, proper planning of traffic signal control systems is critical to maintaining maximum lane capacity.
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In conclusion, this study can be considered a crucial step in traffic management and sustainable transportation at intersections managed by fully actuated signal control systems.

7. Author Contribution Statement

Nihat Can KARABULUT: Conceptualization, literature review, data curation, methodology, software and formal analysis, visualization, original draft preparation. Murat OZEN: writing-review and editing. Oruc ALTİNTASİ: writing-review and editing.

8. Ethics Committee Approval and Conflict of Interest Declaration

“There is no need for an ethics committee approval in the prepared article”
“There is no conflict of interest with any person/institution in the prepared article”

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