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MODELING OF EFFECTIVE PARAMETERS FOR CAPACITY PREDICTION AT SIGNALIZED INTERSECTION LANES

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Abstract. Current capacity manuals do not allow comprehensively evaluating negative effects on lane capacity caused by undisciplined vehicle movements and lane utilization, such as failure to obey distance rules, lane blockage caused by roadside parking effect, formation of an extra lane using in the emergency lane, etc., which are mostly observed in undeveloped and developing countries. Irregularities of the traffic flow caused by undisciplined movements and lane utilization result in decreased capacity or traffic change on the urban lanes. To overcome this problem, a lane-based study was carried out to determine the relation among effective parameters and their effect on lane capacity. In order to model the impact of these parameters, a comprehensive study was conducted in two cities in Turkey. Two different methods (statistical analysis and metaheuristic search algorithm) were used for this purpose and new more reasonable lane capacity estimation models (ALLCEM-1 and ALLCEM-2) were developed by examining all local conditions. The results proved that both examined methods are effective in modelling lane capacity of signalized intersections. It was also found that such parameters as the type of intersection (either a roundabout or not), effective green time, saturation flow rate, traffic volume, heavy vehicle ratio, and the number of actively used lanes have a major impact on the accuracy of prediction of road capacity.

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Introduction

High growth in vehicle numbers in urban areas has caused many traffic congestion-related problems at urban signalized intersections. To solve these problems, researchers and planners constantly develop different analysis methods for signalized intersections. Capacity analysis methods are being developed to address capacity modelling problems, since capacity estimation is crucial in the planning and operation of intersections (Ji and Prevedouros, 2005; Tenekeci et al., 2014). Capacity analysis studies are generally carried out to design and model new intersections or to increase the operational performance of existing intersections. Capacity analysis offers a set of tools for transportation engineers to efficiently design or improve lane capacity. It also helps determine the optimum geometric properties and signal timing necessary to control and manage traffic volumes at intersections (Troutbeck and Akçelik, 1994; Jovanović et al., 2017).

In ideal conditions, the maximum traffic capacity of a signalized intersection is influenced by the geometric properties and timing plan rather than other factors (Minderhoud et al., 1997). In general, intersection capacities are determined by considering such deterministic parameters as road properties, geometry, and signalization conditions. Some other random parameters, such as traffic flow, undisciplined vehicle movements and lane utilization, weather conditions, pedestrian flow characteristics, driver behaviours in particular countries, etc., also have a significant effect. These random effects result in various interactions among the vehicles on the lanes; thus, different capacity properties can be observed. Due to the impact of these parameters, the current lane capacity appears to be lower than the predicted capacity. As a result, capacity loss is often observed at intersections and the entire road network in many undeveloped and developing countries.

In the last few decades, researchers and planners have developed and adopted several road capacity analysis methods (McGhee and Arnold, 1997; MOM, 2006; Tian and Wu, 2006; Zhao et al., 2013; Asgharzadeh and Kondyli, 2018). According to Miller (1968), the first simple model was used by Clayton (1941) to estimate road capacity. Later, Wardrop (1952) and Webster and Cobbe (1966) developed the models to estimate capacity of approach legs and road widths, they were consistently used for capacity estimation. The Highway Capacity Manuals (HCMs) for examining road capacity were developed, improved and updated by the National Cooperative Highway Research Program (NCHRP) and Federal Highway Administration (FHWA) in the U.S from 1950 to 2016. Nowadays, the updated 2016 version of HCM (2010) is still used by the researchers in capacity analysis as a detailed revision of the former HCMs (TRB, 2016). A similar manual used in Australia – aaSIDRA, formally known as SIDRA, first developed by the Australian Road Research Board (ARB) Ltd. – has been widely used in the analysis by the Australian road and traffic authorities (ARTA), as well as academic and research institutions (Troutbeck and Akcelik, 1994). The Malaysian Highway Capacity Manual (2006) was developed based on the HCM (2000) to predict capacity at signalized intersections in Malaysia by evaluating the utilization of the passenger car equivalent (PCE) and adjustment factors (AF), which were modified with regard of the Malaysian traffic characteristics (TRB, 2000; MOM, 2006). Many studies have been previously conducted to predict capacity by considering various road, driver and traffic properties and inputs for intersection geometry optimization and signal timing (Wang et al., 2015). As it may be observed considering the previous studies, some researchers calculated intersection capacities by considering different geometry, traffic flow and environmental characteristics, and they generally used some correction factors to model the capacities of the intersections. For instance, Allen et al. (1998) examined the effect of bikes on intersection capacity by using the capacity discount coefficient. They found that pedestrians and bikes have a considerable impact on capacity. In a similar study, Yoassry and Benekohal (2000) compared 1994 and 1997 versions of HCM to determine the delay of vehicles at intersections by evaluating saturation flow rate and different correction coefficients for lanes. In another study, Jing and Wang (2004) investigated the effects of the conflict points in mixed traffic conditions on intersection capacity. They found that conflicts among pedestrians, bikes, and vehicles are the reason for different distances in the car-following state, they also concluded that conflicts among road users have a great effect on capacity. In yet another study, Huang et al. (2008) aimed to determine the effects of the time headway distribution characteristics. In their research, they demonstrated that the time headway distribution characteristics cause congestion due to formation of queues at signalized intersection approaches. Aydın et al. (2022) also conducted a study to evaluate the performances of the current models discussed in the literature. They found that the results of the current models cannot properly reflect all traffic flow properties. Thus, they proposed that if countries have not developed original dedicated models for the analysis, they should modify the existing models for their own needs considering the local traffic conditions. The updated HCM (2016) model was adopted as the most frequently used method to investigate the effects of various parameters, such as lane width, heavy vehicle ratio, road grade, parking facilities, bus blockage, lane utilization, weather conditions, driving behaviours, light conditions, etc. Some correction factors were considered to evaluate their effects in calculations (Yang et al., 2008; Rahman et al., 2008; Tang et al., 2013; Lindsey et al., 2014). As it can be seen from the current literature, signalized intersection capacity analysis procedures and methodologies are being continually reviewed and updated by many researchers from all around the world with the ultimate aim to prevent long vehicle queues and delays. In all studies, the general aim is to maximize the potential capacity of examined intersections to increase traffic-carrying capacity of intersections (Li, 2011; Ma et al., 2017; Grigonis et al., 2020).

Nowadays, many traffic experts, researchers and planners from many countries use different manuals, such as HCM (United States), SIDRA (Australia), MHCM (Malaysia), CCG (Canada) etc. to estimate road capacity (TRB, 2010; 2016; Troutbeck and Akçelik, 1994; MOM, 2006; Teply et al., 2008). At the same time, various capacity manuals offer slightly different methods for the analysis due to different traffic, road and driving characteristics typical of various countries. Therefore, many studies on estimation design methods must be conducted in order to offer the most efficient procedures (Abidin, 2007). Local engineers and practitioners in many undeveloped or developing countries commonly use the manuals of developed countries, such as HCM, SIDRA, CCG, etc. when designing their signalized intersections due to the lack of their own manuals. Based on the results of the previously conducted studies, this is not the most efficient procedure because the traffic, road, and driving characteristics of each country differ as compared to other countries. Thus, it is expedient to conduct special studies in each particular country considering the local traffic conditions. For example, in Turkey, the methods suggested by HCM and SIDRA are commonly used by road authorities and planners in capacity analysis. However, these manuals were developed considering the traffic, road, and driver characteristics of the respective countries. Therefore, popular capacity manuals may not be appropriate for the analysis of signalized intersections and local road networks in Turkey.

Previous studies conducted in many countries clearly show that there are various effective parameters to be considered analysing signalized intersections (Aydın and Topal, 2018). Unfortunately, currently used manuals do not allow comprehensively evaluating negative effects of undisciplined illegal vehicle movements and lane utilization (e.g., lane blockage caused by roadside parking, failure to obey distance rules, formation of an extra lane, etc.) on estimation of capacity of lane intersections. To prevent this problem, a lane-based study was carried out to determine the relation among various parameters and their impact on intersection lane capacity (*c*) at different legs. For this purpose, all effective and common factors from the signalized were determined and then statistical analysis and swarm intelligence-based metaheuristic algorithm were used to propose a lane-based model by considering negative effects of various parameters. Therefore, lane-based signalized intersection lane capacity estimation models (ALLCEM-1 and ALLCEM-2) were developed by using two different modelling methods (statistical analysis and metaheuristic search algorithm) based on observation data at various sites. The author tried to answer the question of "how intersection capacity can change depending on various effective parameters in a developing country?" by proposing new lane-based capacity estimation models. The proposed models were developed using many parameters that directly affect the capacity. The models can be used to address such challenges as traffic chaos, long traffic delays, and accidents caused by insufficient capacity conditions.

1. Study site and data collection

In the study, a comprehensive data collection process was performed to determine the relation among various parameters and their impact on signalized intersection (SI) lane capacity (*c*) at different signalized intersection legs by considering undisciplined illegal vehicle movements and lane utilization. For this purpose, lane-based data set was collected from the total of six different signalized intersections (including four-legged, four-legged roundabout and three-legged roundabout) named as SI 1-6, which were chosen to examine, analyse and model lane capacity in two different cities (Antalya and Trabzon) of Turkey. Locations of the examined cities are shown in Figure 1.

These signalized intersections are located on the main arterials of Antalya and Trabzon city centres. The data collection process was repeated at different times in winter and summer seasons to reflect seasonal differences. All data were collected by using site observations and video recordings. Cameras were placed in high locations. Hence, drivers could not notice that the observation and recording took place and showed their normal driving behaviours (Figure 2). Video recordings and site observations were made between 07:00–08:30 and 17:00–18:30 (peak) hours on the weekdays. Within the scope of this study, the most common intersection types (four-legged, four-legged roundabout and three-legged roundabout) were chosen randomly in different locations of the two examined cities to reflect on different signalized intersection characteristics. Only approach leg parameters (lane number, volume, etc.) of all intersection types were compared with each other. To reach the aim of the present study, traffic volume and movements inside the intersections were not evaluated to prevent confusion in comparison by intersection type.

Analysis data were obtained manually by watching recordings in the traffic laboratory. During the physical observation, a digital counter program was used and all data were extracted by counting. Lane-based data extraction was the most important stage in the data mining process. In the extraction process, each data set was obtained by analysing every leg lane separately. Hence, lane-based data were obtained and used in the analysis. The following data were obtained from site observations and video recordings in the laboratory:

- Traffic volumes, veh/hr/lane;
- Number of actively used lanes (used lanes on intersection legs after lane blockage caused by roadside parking effect on the shoulder lane or formation of an extra lane when the emergency lane was used for movement);
- Vehicle number in the queue in the red phase per lane, veh;
- Circle (traffic light cycle time) and phase times of the signalized intersections, sec;
- Vehicle ratio (%, proportion of passenger cars, minibuses, buses and trucks) in urban traffic flow for all legs and lanes;

Figure 1. Locations of the two examined cities and some sample visuals from the signalized intersections

- Number of vehicles passing in the green time, veh/lane/green phase;
- Actual green time, yellow change and red clearance interval, and clearance lost time, sec;
- Intersection properties (intersection type, leg and effectively used lane, etc.).

Counting the vehicles manually, the movements of the total of 56 760 vehicles (42 241 passenger cars, 9367 minibuses, 3237 buses and 1915 trucks) were examined at 6 different signalized intersections. To gain a better understanding of the collected data, the properties of the obtained data were categorized and summarized as shown in Table 1.

It can be observed considering the data on the examined intersections that if an intersection leg has 4 lanes, Lane 4 is used only for left turn. If a leg has 3 lanes or fewer, the highest lane numbers (Lane 3 or 2) is used for through and left at the same time. If a leg has 4 lanes or fewer lanes, the lowest lane number (Lane 1) is used for the through and right turn at the same time according to intersection design. To understand intersection properties and geometric features, the layouts of all six intersections are given in Figure 3.

Figure 2. Some sample visuals from data collection process at the examined signalized intersections

Table 1. Information about the collected data and examined signalized intersections

Intersection No	Intersection Type	Leg No (L_{no})	Designed number of lanes	Number of actively used lanes (AUL_N)	Cycle time (C), sec	Vehicle Ratio (P_V) $P_{p.car}$ %	$P_{minibus}$ %	P_{bus} %	P_{truck} %	Average vehicle number in queue (N_V), veh
SI 1	Four-legged	L-1	3	3+1 Illegal Use	160	69.7	22.0	6.5	1.8	10
		L-2	3	3+1 Illegal Use		70.8	19.1	9.0	1.1	13
		L-3	2	2		80.8	15.1	4.0	0.1	10
		L-4	2	2		79.3	14.1	6.6	0.0	5
SI 2	Four-legged	L-1	3	3+1 Illegal Use	210	73.8	17.5	6.2	2.5	13
		L-2	3	3		64.4	24.4	4.0	7.2	11
		L-3	2	2		77.7	18.5	3.5	0.3	12
		L-4	2	2		80.9	12.1	6.0	1.0	8
SI 3	Four-legged	L-1	3	3-1 Illegal Parking	171	76.3	17.1	6.6	—	12
		L-2	2	2		77.5	14.4	8.0	0.1	12
		L-3	2	2		69.9	21.5	7.5	1.1	6
		L-4	2	2		79.5	13.8	6.0	0.7	6
SI 4	Three-legged Roundabout	L-1	3	3	165	72.7	12.6	4.2	10.5	11
		L-2	3	3		69.3	16.5	4.6	9.6	11
		L-3	2	2+1 Illegal Use		76.4	16.2	1.3	6.1	10
SI 5	Four-legged Roundabout	L-1	3	3	158	78.2	10.5	6.2	5.1	6
		L-2	3	3		73.5	11.0	9.6	5.9	6
		L-3	2	2		83.3	8.4	6.2	2.1	7
		L-4	2	2+1 Illegal Use		90.1	5.5	3.0	1.4	5
SI 6	Four-legged Roundabout	L-1	3	3-1 Illegal Parking	102	70.9	22.2	5.5	1.4	9
		L-2	2	2		77.2	15.8	5.2	1.8	12
		L-3	1	1		81.1	10.7	7.0	1.2	202
		L-4	2	2		73.5	18.7	6.3	1.5	10

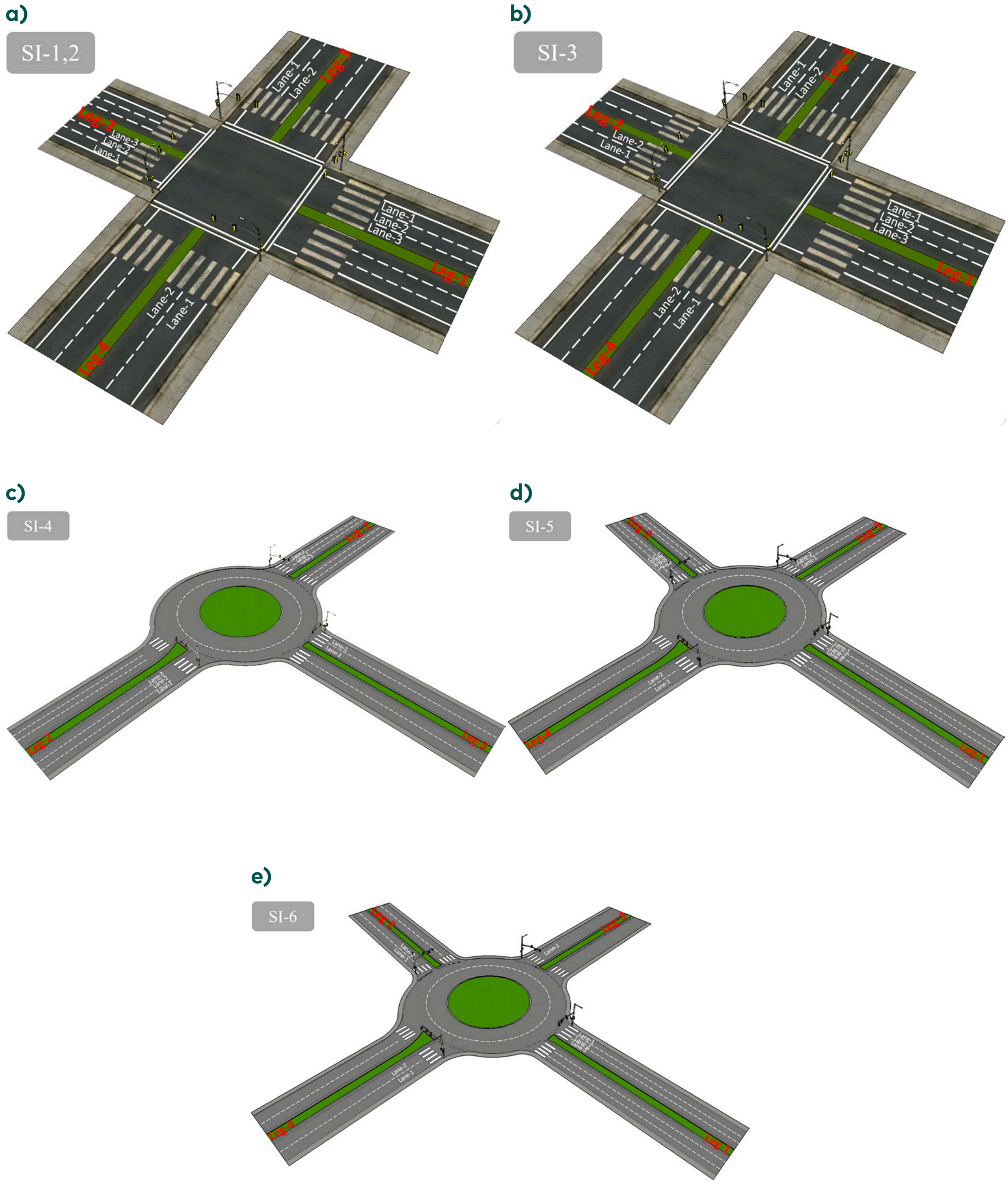

Figure 3. Schematic layout of signalized intersections: (a) SI 1-2, (b) SI 3, (c) SI 4, (d) SI 5, and (e) SI 6

In the course of study, the author aimed to examine and analyse the most common and used intersection types in Turkey as a developing country. As it can be seen from Table 1, all examined intersections have different characteristics. The results presented in the table also contribute to reaching the aim of the study. The measured lane-based traffic volumes for all intersection legs are also given in Figure 4.

As it can be seen from Figure 3, traffic volumes per lane may show changes at all intersection legs depending on the characteristics of the intersections, such as the number of the leg and used lane, vehicle arrival rate, driver characteristics, vehicle type, etc. It was also observed that the average lane volumes at a three-leg roundabout demonstrate close values for each leg. Figure 4 also shows that only legs of SI-4 (Signalized Intersection-4) have similar average volumes and average leg lanes of other intersections demonstrate significant differences. This result implies that lane-based average leg volumes of a three-legged roundabout show lower differences compared to the four-legged intersections.

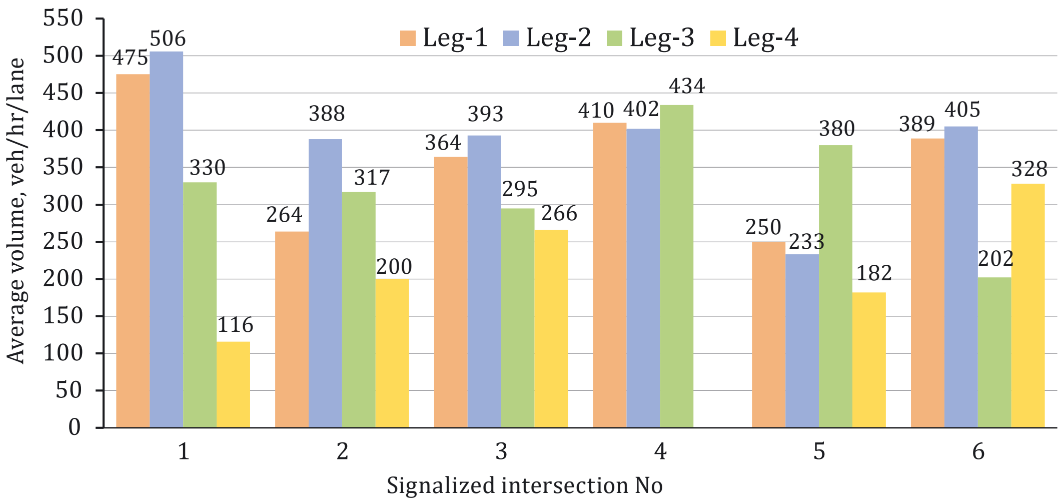

Figure 4. Measured average lane volumes for each examined intersection leg

2. Analysis of capacity parameters

Signalized intersection lane capacity is an important indicator that provides information about the performance of the intersection. In the study, lane capacities (c) for each leg at different intersections were calculated with the help of Equation 1 suggested by HCM (TRB, 2016):

$$c = \sum s \frac{g}{C}, \tag{1}$$

where:
c – capacity, veh/hr;
s – saturation flow rate, veh/hr;
g – effective green time, sec;
C – circle time, sec.

In Equation 1, saturation flow rate s is the flow rate per lane where vehicles on each lane can directly cross the signalised intersection. According to the 2016 version of HCM, saturated flow refers to the number of vehicles that can pass the intersection continuously within the green time for an hour (TRB, 2016). This ratio can be calculated using the formula given in Equation 2. In order to calculate s, the follow intervals (saturation headways) in all lanes of signalised intersection legs lanes were determined first and then s values were calculated for each lane. In the course of calculation, s values of all lanes were analysed separately. According to HCM, s value reaches its maximum value 10 to 14 sec after the green time in a signal (TRB, 2016). This corresponds approximately to the fourth to sixth vehicle in the queue for each lane. In the scope of this study, saturation headways after the fifth vehicle in the queue were used in the calculations of the saturation flow as recommended by HCM (TRB, 2016).

$$s = \frac{3600}{h}, \tag{2}$$

where:
s – saturation flow rate, veh/hr;
h – saturation headway, sec.

In Equation 1, effective green time g can be calculated by using Equation 3 as given below:

$$g = G + Y + R - \left(l_1 + l_2\right), \tag{3}$$

where:
g – effective green time, sec;
G – actual green time, sec;
Y – yellow change interval, sec;
R – red clearance interval, 2 sec;
l_1 – start-up lost time, 2 sec;
l_2 – clearance lost time $Y + R - e$, sec;
e – extension of effective green = 2.0, sec.

Effective green time g for all lanes was directly measured from the site observations and g values were obtained and used in analysis for all lanes at signalized intersections legs separately.

In the analysis, intersection traffic flow and operation parameters per lane were obtained by analysing site recordings. Additionally, lane capacity (c) and saturation flow rate (s) at different intersection legs were calculated using HCM equations (TRB, 2016) as given in Equations 1–2. According to site measurements and calculations, the relation between traffic volume (v) and capacity (c) values (veh/hr/lane) for each signalized intersection leg lane were obtained as shown in Figure 5.

There is a relation between lane volume (v) and capacity (c) on the examined intersection legs (Figure 5). The model coefficient of the calculated lane capacity and measured volume values have high coefficients of determination (R^2), so it means that there is a strong correlation between them. Thus, it can be concluded that a lane-based capacity calculation model can be developed to examine capacity and this result supports the study aim. Therefore, different analysis methods, namely, Ordinary Least Square regression and Artificial Bee Colony algorithm, were used to model lane-based capacity to evaluate the effects of undisciplined lane utilization and some other parameters on capacity. All measured and calculated parameter values are given in Table 2 to gain a better understanding of the obtained data.

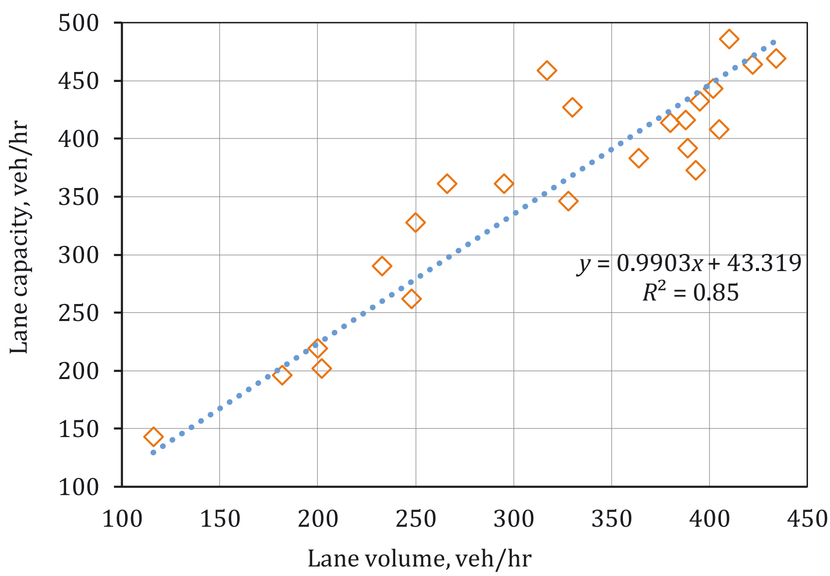

Figure 5. The relation between volume (v) and capacity (c) values on the examined intersection leg lanes

Table 2. Obtained traffic flow data from the site measurements and calculations

Intersection No	Intersection Type	Leg No (L_{no})	Number of actively used lanes in each direction (AUL_N)	Average number of vehicles passed during green time (N_p) veh/lane/green phase: Min. ($N_{p\ min}$)	Max. ($N_{p\ max}$)	Weighted Mean ($N_{p\ w,mean}$)	Average volume ($\bar{v}$) veh/hr/lane	$\overline{(v/c)}$
1	Four-legged	L-1	3+1 Illegal Use	7	26	8	475	0.91**
		L-2	3+1 Illegal Use	11	26	10	506	0.91**
		L-3	2	9	20	8	330	0.77*
		L-4	2	1	10	4	116	0.81*
2	Four-legged	L-1	3+1 Illegal Use	15	38	14	264	0.95***
		L-2	3	16	34	13	388	0.93**
		L-3	2	7	33	11	317	0.69*
		L-4	2	2	10	4	200	0.91**
3	Four-legged	L-1	3+1 Illegal Use	10	36	11	364	0.95***
		L-2	2	15	31	13	393	1.05****
		L-3	2	9	20	8	295	0.82*
		L-4	2	1	10	4	266	0.74*
4	Three-legged Roundabout	L-1	3	6	18	8	410	0.84*
		L-2	3	8	21	9	402	0.91**
		L-3	2+1 Illegal Use	2	13	5	434	0.93**
5	Four-legged Roundabout	L-1	3	5	17	7	250	0.76*
		L-2	3	7	20	8	233	0.80*
		L-3	2	8	21	9	380	0.92**
		L-4	2+1 Illegal Use	7	17	8	182	0.93**
6	Four-legged Roundabout	L-1	3-1 Illegal Parking	4	13	6	389	0.99***
		L-2	2	6	15	7	405	0.99***
		L-3	1	7	13	7	202	1.00***
		L-4	2	4	13	6	328	0.95***

Note: *under capacity, **close to full capacity, ***unstable flow results,
****the demand exceeds the available capacity

In Table 2, the majority of the examined intersection leg lanes demonstrate undersaturated flow conditions (v/c ratio < 0.85 or between 0.85–0.95). According to HCM v/c ratio threshold descriptions, these results show that the lanes are generally operating under capacity and longer delays may be expected, but continuously increasing queues should not form (TRB, 2016). However, in some leg lanes, v/c ratio is between 0.95–1.0, which means that lane improvements will soon be required to prevent high delays at these intersections. It can also be seen from Table 2 that only lanes of SI-3 L-2 have oversaturated conditions and almost all of the examined intersection legs are working in undersaturated or saturated flow conditions, so oversaturated flow conditions do not affect intersections negatively for the modelling process. All data obtained from the measurements and calculations to be used in both OLR analysis and ABC optimization model analysis are summarized in Table 3.

Table 3. Data obtained from the measurements and calculations used in the OLS regression and ABC optimization modelling analysis

Intersection		Leg No (L_{no})	Lane 1					Lane 2					Lane 3					Lane 4				
No	Type		ν	N_V	g	N_{HV}	s	ν	N_V	g	N_{HV}	s	ν	N_V	g	N_{HV}	s	ν	N_V	g	N_{HV}	s
1	Four-legged	L-1	252	5	59	15.1	1710	627	15	59	10.1	1098	545	11	59	5.0	1636	155	7	20	2.9	1714
		L-2	355	9	58	16.2	1235	644	15	60	11.3	1440	518	16	20	9.1	1326	172	6	21	3.8	1800
		L-3	283	9	40	4.3	1440	376	10	40	3.9	1385	—	—	—	—	—	—	—	—	—	—
		L-4	111	5	20	5.2	1800	121	5	20	8.0	2000	—	—	—	—	—	—	—	—	—	—
2	Four-legged	L-1	155	6	111	16.6	1658	329	17	110	10.1	1440	307	15	111	4.2	1385	202	6	29	3.9	1714
		L-2	415	11	86	16.5	1161	600	16	86	12.0	1636	148	5	86	5.0	1895	—	—	—	—	—
		L-3	292	11	55	4.3	1125	341	13	55	3.3	1432	—	—	—	—	—	—	—	—	—	—
		L-4	175	7	15	8.8	1896	225	8	15	5.1	1912	—	—	—	—	—	—	—	—	—	—
3	Four-legged	L-1	332	11	36	8.1	1501	396	12	36	5.0	1408	—	—	—	—	—	—	—	—	—	—
		L-2	312	10	37	7.2	1440	473	13	37	9.0	1565	—	—	—	—	—	—	—	—	—	—
		L-3	285	4	37	9.1	1398	305	7	38	8.0	1326	—	—	—	—	—	—	—	—	—	—
		L-4	265	5	37	7.3	1203	266	7	37	6.1	1258	—	—	—	—	—	—	—	—	—	—
4	Three-legged Round-about	L-1	387	12	45	21.1	1602	431	11	47	12.0	1506	411	10	47	11.1	—	—	—	—	—	—
		L-2	346	11	61	19.2	1486	545	12	62	13.1	1440	316	11	63	10.3	—	—	—	—	—	—
		L-3	445	13	40	9.0	1098	475	3	41	5.0	1236	383	14	41	8.1	—	—	—	—	—	—
5	Four-legged Round-about	L-1	174	3	33	16.0	1806	303	7	33	12.0	1308	273	8	34	6.0	—	—	—	—	—	—
		L-2	139	3	31	23.2	1906	286	7	33	15.1	1480	273	7	33	8.1	—	—	—	—	—	—
		L-3	352	6	45	9.3	1555	408	7	45	7.2	1213	—	—	—	—	—	—	—	—	—	—
		L-4	179	4	25	5.4	1881	205	5	25	4.0	1726	161	5	26	3.9	—	—	—	—	—	—
6	Four-legged Round-about	L-1	380	8	19	7.7	1598	398	9	18	6.0	1333	—	—	—	—	—	—	—	—	—	—
		L-2	375	12	19	8.8	1445	435	11	19	5.1	1501	—	—	—	—	—	—	—	—	—	—
		L-3	202	8	17	8.2	1612	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
		L-4	314	9	23	9.6	1384	342	10	23	6.0	1298	—	—	—	—	—	—	—	—	—	—

Note: ν – volume, veh/hr; N_ν – avg. vehicle number in the queue at the beginning of green time, veh; g – effective green time per lane, sec; R_{HV} – heavy vehicle ratio per lane; s – saturation flow rate, veh/hr.

3. Model development for lane capacity

3.1. Variable selection

In the study, the total of eight different data types were collected as independent variables to be used in the Ordinary Least Square (OLS) regression analysis. They were categorized as covariates and dummy according to their properties. As mentioned in the previous sections, lane-based capacity analysis is affected by various parameters, such as actively used lane number, number of surrounding vehicles (volume), queue length on the lane, effective green time, heavy vehicle ratio, saturation flow rate, study site and signalized intersection type. For the analysis, actively used lane number, study site (for the evaluation of driving behaviours) and intersection type data were determined by examining the properties of the study site. All remaining data (traffic volume, queue length on the lane, effective green time, heavy vehicle ratio, and saturation flow rate) were obtained by analysing video recordings in detail. All obtained data for the analysis using both models are summarised in Table 4.

Table 4. Dependent and independent variables of the developed OLS regression model

Dependent variable	
c	Lane capacity of signalized intersection legs, veh/hr
Covariates	
AUL_N	Actively used lane number
ν_L	Traffic volume per lane
N_ν	Average vehicle number in queue per lane
g	Effective green time per lane
R_{HV}	Heavy vehicle ratio per lane
s	Saturation flow rate per lane, veh/hr
Dummy variables	
E_{G2}	(If examined city is Antalya: 1, otherwise: 0)
SI_{T2}	(If intersection type is three-legged roundabout: 1, otherwise: 0)
SI_{T3}	(If intersection type is four-legged roundabout: 1, otherwise: 0)

3.2. Modelling intersection leg lane capacity using OLS regression

In the study, a multiple OLS regression method was used to examine and model the relation between lane capacity (c) of intersection legs and the parameters influencing the capacity. For this purpose, the total of 56 760 vehicles (passenger cars: 74.42%, minibuses: 16.50%, buses: 5.70% and trucks: 3.37%) were investigated. The coefficients of the regression model were defined as the change in the expected value of associated with a one-unit increase in an independent variable with the other independent variables held constant in the analysis (Table 4). Disturbances of the model were accepted as distributed normally based on the Central Limit Theorem (CLM). Additionally, Shapiro-Wilk W Normality Test was also conducted in the analysis to investigate whether disturbances are really normally distributed. Multicollinearity, heteroscedasticity and model specification error problems were also investigated by using diagnostic tests to verify that the examined model is valid.

In the OLS regression, the developed leg lane capacity (c) estimation model 1 (ALLCEM-1) includes qualitative and quantitative variables as given in Table 5, it is named Analysis of Covariance (ANCOVA) model. The formula of the suggested model can be written as given in Equation 4.

$$c = a_0 + a_1 E_{C2} + a_2 SI_{T2} + a_3 SI_{T3} + b_1 L_{\mathrm{N}} + b_2 V_L + b_3 N_{\mathrm{V}} + b_4 g + b_5 R_{\mathrm{HV}} + b_6 s + \varepsilon, \quad (4)$$

where:
c – lane capacity of signalized intersection legs (veh/hr);
a_0 – a constant term of the model;
a_i – used dummy variables ($i \neq 0$);
b_j – coefficients of the determined variables in the model j = 1,..., 6;
ε – disturbance term of the model.

To calculate the coefficient of Equation 4, an OLS estimator was used and multicollinearity, heteroscedasticity, and model specification error problems were investigated using diagnostic tests. Analysis results are summarised in Table 5. After controlling all problems, disturbances are accepted as distributed normally due to a vast number of vehicles (42 241 passenger cars, 9367 minibuses, 3237 buses and 1915 trucks) based on the CLM (Mert, 2016; Aydın, 2022). It may be seen from the table that the suggested model is significant (F = 46.15; P = 0.000 < 0.01 and R^2 = 0.851) and disturbances of the model are distributed normally according to Shapiro-Wilk W Test.

Table 5. Results of the predicted model for the lane capacity (*c*) of signalized intersection legs

Variables	Coefficient†	Std. E.	*t*	*P* value†
Dependent Variable: (*c*)				
a_0	221.55	35.2	6.29	0.000*
E_{G2}	–10.72	8.1	–1.34	0.187
SI_{T2}	–2.13	1.5	–1.41	0.091***
SI_{T3}	–4.69	3.2	–1.45	0.095***
AUL_N	–19.84	9.7	–2.04	0.046**
ν_L	0.61	0.1	5.86	0.000*
N_V	3.36	3.2	1.03	0.306
g	4.09	0.5	7.52	0.000*
R_{HV}	0.58	0.1	3.34	0.000*
s	76.62	29.8	2.57	0.013**
Max. VIF	4.2 < 10 (there is no multicollinearity problem)			
White Test	P = 0.326 > 0.10 (there is no heteroscedasticity problem)			
Shapiro-Wilk W Test	P = 0.182 > 0.10 (disturbances of the model are normally distributed)			
Ramsey Reset Test	P = 0.256 > 0.10 (model have no model specification error problem)			
Note: n: 56760; $F(8, 56)$; 46.15; $P < F$: 0.000				

†*** Significant at 0.10 level, ** Significant at 0.05 level, *Significant at 0.01 level.

Results show that both types of intersections (three-legged and four-legged roundabouts) have significant and negative effects on the predicted lane capacity (c) of intersection legs (coeff. < 0; P < 0.10) because long vehicle queues in the roundabouts have a negative effect on capacity. On the other hand, four-legged intersections have significant and positive effects on lane capacity because they do not have a circle and so there are no large vehicle queues in the centre of the intersection. It was also observed that actively used lane number (AUL_N) variable has a negative effect on the predicted lane capacity (c). It means that if the number of actively used lanes increases, lane capacity will show decrease, on the contrary. The variables, lane-based traffic volume (ν_L), effective green time (g), heavy vehicle ratio (R_{HV}) and saturation flow rate (s) have also positive and significant effects on prediction of lane capacity (c) (coeff. > 0; P < 0.10). It means that the presence of different flow and signal timing characteristics at intersections has positive and significant effects on prediction of (c). It was also determined that city characteristics have not had any significant effect. It means that data collection from different cities does not have a significant effect

($P > 0.10$) and drivers in both cities demonstrate similar characteristics (homogeneous driver distribution). According to results, the average number of vehicles in queue (N_V) per lane variable does not have a statistically significant effect on capacity calculation. It means that the number of vehicles in queues at intersection legs did not have any effect on capacity. Thus, it can be concluded that the number of actively used lanes is more significant for the capacity analysis of lanes at legs than the number of vehicles in queues.

3.3. Modelling of intersection leg lane capacity using ABC algorithm

In the modelling, Artificial Bee Colony (ABC) algorithm method was used as the second method to examine and model (ALLCEM-2) intersection leg lane capacity. ALLCEM-2 developed by using the HCM includes many parameters that were modified based on traffic and intersection characteristics. Within this scope, modelling of leg lane capacity (c) was determined as the objective of the study. The flow chart of the used ABC algorithm is given in Figure 6.

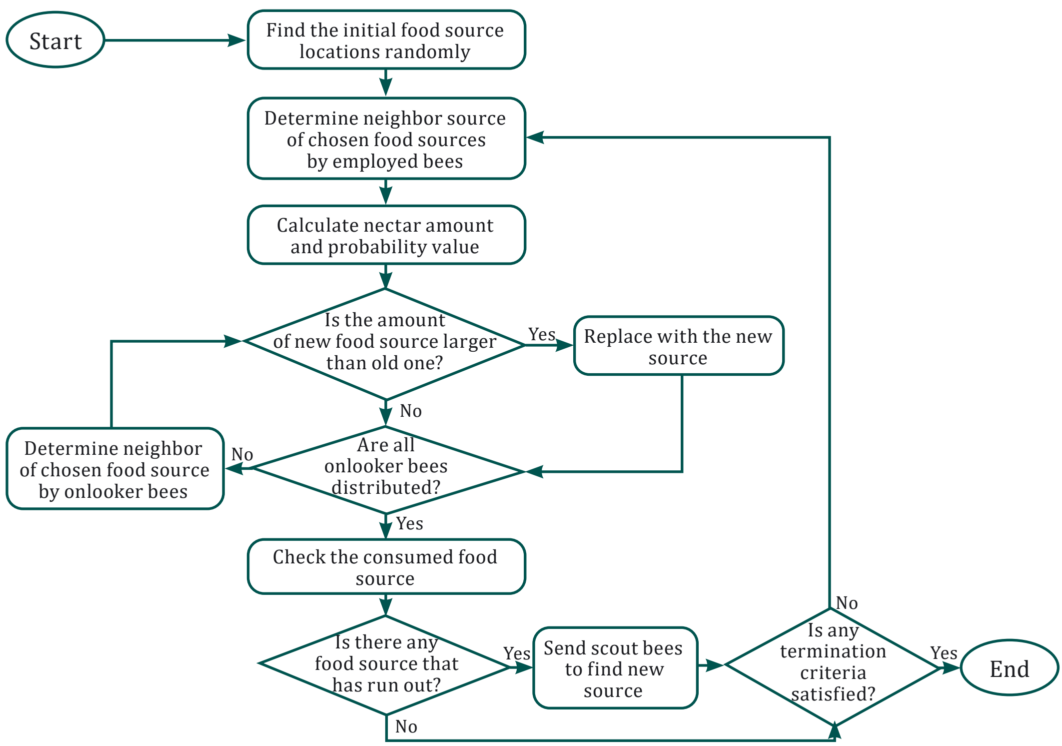

Figure 6. The flow chart of the used ABC algorithm in the model

In the modelling stage, statistically significant parameters, such as actively used lane number (AUL_N), traffic volume per lane (V_L), heavy vehicle ratio per lane (R_{HV}) and signalized intersection type ($SI_{T_{1-3}}$) were examined. Also, effective green time per lane (g), saturation flow rate per lane (s) and circle time (c) of the signalized intersections were used as fundamental parameters in Equation 5. The equivalents of the used parameters in model analysis can be specified in Table 6 for the examined problem.

In the analysis, the population size and maximum iteration numbers were taken as 50×100 and 10 000, respectively. In each algorithm, the stopping criteria was to complete the search process when the maximum number of generations was obtained (assumed as 10 000 generations) or $\left|f(\vec{x})_{\max} - f(\vec{x})_{\min}\right| < 10^{-4}$ where $f(\vec{x})$ was objective function value. The equation of the suggested model can be expressed by Equation 5.

$$C_{LB} = \sum s\frac{g}{c} - 10.45L_N^{3.18} - 1.58V_L^{0.93} - 1.5R_{HV}^{12.02} + 31.88SI_{T1} + \\ + 66.99SI_{T2} + 65SI_{T3}, \quad (5)$$

where:
c – lane capacity of signalized intersection legs, veh/hr;
s – saturation flow rate, veh/hr/lane;

Table 6. The equivalents of the used parameters in ABC model

No	Process Steps in ABC Algorithm	Equivalents of the Process Steps in ABC Algorithm
1	Food source	Suggestion of new model for lane capacity (c) of signalized intersection legs
2	Location of food source	Parameters used in the suggested model
3	Nectar amount in the food source	The scope of the calculated error in the suggested capacity model
4	Onlooker bees search neighbour food sources	Updating the weight coefficients in the suggested capacity model
5	Design pool	The database in which all information about for the suggested capacity model in the algorithm is stored
6	Greedy selection	The replacement of the old model with the updated new capacity model
7	Food limit	The number of times the suggested model can stand in the algorithm without self-renewal
8	Scout bees search new food source	Replacement of old model with the new suggested capacity model (if old model exceeds the food limit)
9	Repetition of all process	Creating or updating the suggested model
10	Determination of food source which has maximum amount of nectar	Suggested new capacity model with minimum error value (optimum result).

g – effective green time per lane, sec;
C – circle time, sec;
$\mathrm{AUL_N}$ – actively used lane number;
V_{L} – volume, veh/hr/lane;
R_{HV} – heavy vehicle ratio per lane;
SI_{T_i} – observed level of service (i = 1, 2 and 3).

To measure the performance of ALLCEM-2 model, three error measuring parameters were used, named mean absolute percentage error (MAPE, %), mean absolute error (MAE), and root mean square error (RMSE), as given in Equations 6–8, respectively. All three error measuring methods define the variation between the predicted and actual data set which signifies the developed ALLCEM-2 model's accuracy as shown in Table 7.

$$\mathrm{MAPE}(\%) = \frac{\sum_{i=1}^{n}\left|\frac{R_i - P_i}{R_i}\right|}{n} \times 100, \tag{6}$$

$$\mathrm{MAE} = \frac{\sum_{i=1}^{n}\left|P_i - R_i\right|}{n}, \tag{7}$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - R_i)^2}{n}}, \tag{8}$$

where:
MAPE – Mean Absolute Percentage Error, %;
MAE – Mean Absolute Error;
RMSE – Root Mean Square Error;
R_{i} – calculated lane capacity values, sec;
P_{i} – predicted lane capacity values, sec;
N – data numbers (leg numbers).

In Table 7, MAE, RMSE and MAPE, %, values between the actual and predicted values were calculated as 20.42, 20.61 and 6.19 %, respectively. Error results show that the developed ALLCEM-2 model can be used in analysis because the calculated (c_{c}) and predicted (c_{p}) capacity values are found to be close to each other. It means that there is no great difference between them and lane capacity estimation using the developed model.

The distributions of c_{c} and c_{p} lane capacity values were obtained from site observations, calculations and developed model estimations. The relation between the calculated and predicted capacity values for lanes and legs are shown in Figure 7, a–b. Additionally, the relation among the calculated capacity, predicted capacity and leg volume values are shown in Figure 8, a–b.

As seen from Figure 7, a–b, there are strong relations among the calculated and predicted lane and leg capacities, respectively. The model coefficients of the calculated and predicted capacities have high determination (R^2) values, so it can be concluded that capacity calculations and predictions for the lanes and legs have similar and correct results. The same strong relations can also be seen from

Table 7. MAPE, %, error for the calculated and predicted lane capacity values in ALLCEM-2 model

Intersection		Leg No (L_{no})	Lane capacity of intersection legs, veh/hr/lane			MAE	RMSE	MAPE, %
No	Type		Calculated (c_c)	Predicted (c_p)	|Difference| (c_d)			
1	Four-legged	L-1	432	417	15	20.25	20.59	7.17
		L-2	464	489	25			
		L-3	427	446	19			
		L-4	143	165	22			
2	Four-legged	L-1	262	239	23	17.25	17.66	5.86
		L-2	416	401	15			
		L-3	459	472	13			
		L-4	219	201	18			
3	Four-legged	L-1	383	361	22	21.25	21.25	5.75
		L-2	373	352	21			
		L-3	361	382	21			
		L-4	361	340	21			
4	Three-legged Roundabout	L-1	486	510	24	22.00	22.11	4.73
		L-2	443	420	23			
		L-3	469	450	19			
5	Four-legged Roundabout	L-1	328	308	20	19.25	19.37	6.61
		L-2	290	268	22			
		L-3	414	433	19			
		L-4	196	212	16			
6	Four-legged Roundabout	L-1	392	371	21	22.50	22.69	7.01
		L-2	408	381	27			
		L-3	202	183	19			
		L-4	346	369	23			
Mean Error ($\bar{X}$)						20.42	20.61	6.19

Figure 8, a–b that there are similar and related results among the calculated capacities, predicted capacities and volumes for examined signalized intersection legs. All these findings support the accuracy of the developed capacity estimation model by using ABC algorithm.

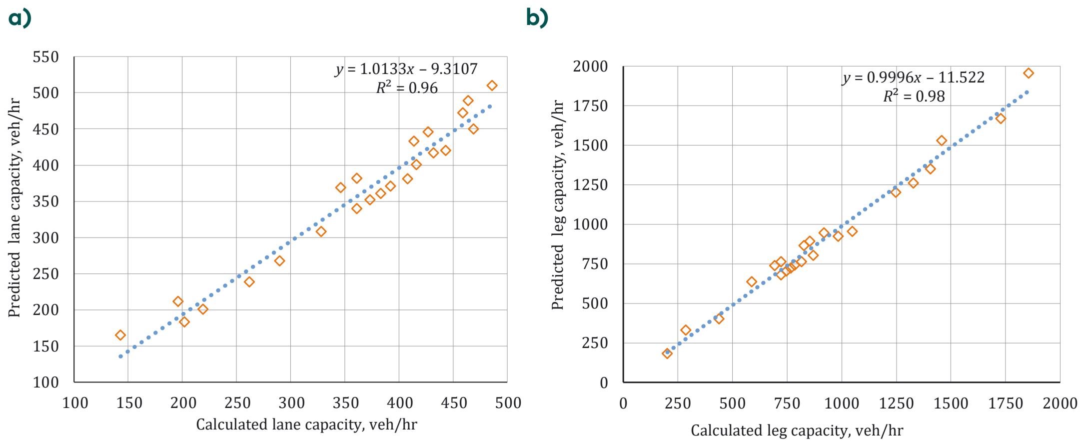

Figure 7. The relation between the calculated (c_c) and predicted (c_p) capacity values for intersection lanes and legs

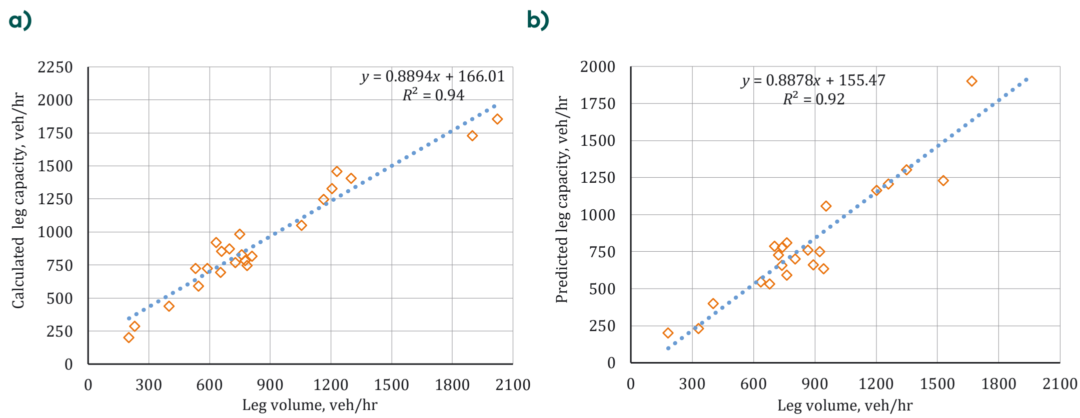

Figure 8. Calculated-predicted capacities and volumes for signalized intersection legs

Conclusions and suggestions

Within the scope of this study, two new models (ALLCEM-1 and ALLCEM-2) were developed to estimate the capacity of signalized intersection leg lanes using statistical analysis and metaheuristic algorithm methods. For this purpose, different intersection data were collected to understand capacity change along various observed effective parameters. Hence, two different lane capacity estimation models were developed by evaluating all effective and important factors. Based on the results of the modelling analysis, the following conclusions have been drawn:

- The used methods based on OLS regression and ABC algorithm were found effective to investigate and model intersection lane capacity (c) at different intersection legs by evaluating various parameters ($F = 46.15$; $P = 0.000 < 0.01$ and $R^2 = 0.851$ for ALLCEM-1 model and average MAE = 20.42, RMSE = 20.61 and MAPE = 6.19 % for ALLCEM-2 model).
- According to ALLCEM-1 model, all intersection types have a statistically significant effect on lane capacity estimation. Results also indicated that roundabout intersection types (three or four-legged) have a negative and the four-legged type has a positive effect on lane capacity. Therefore, ALLCEM-1 model results confirm that standard four-legged intersections give more accurate results for the estimation. In ALLCEM-2 model, this positive effect was found for all intersection types. In conclusion, the presence or absence of a roundabout has a great effect on the intersection capacity for both models and it clearly demonstrates that if undisciplined movements and lane utilization exist on the approach legs, lane-based capacity calculation can be a good approach for the analysis.
- Such parameters as effective green time (g) and saturation flow rate (s) also have positive effects on lane capacity (c) prediction for both developed models. On the other hand, lane-based traffic volume (ν_L) and heavy vehicle ratio (R_{HV}) have a positive effect only for ALLCEM-1 model and a negative effect for ALLCEM-2 model. It means that models may show different results for some parameters. Commonly, both models mutually define all examined parameters as important and effective parameters for the estimation.
- As mentioned in the previous studies (Gunay, 2004; Ben-Edigbe, 2005; Gunay, 2009; Aydin and Topal, 2016), in many undeveloped and developing countries, drivers generally do not observe a lane-based-driving discipline depending on the number of the actively

used lane and lane width. Thus, it causes a serious capacity loss on the lanes and legs, and current capacity models are not capable to evaluate this situation. At the same time, ALLCEM-1 and ALLCEM-2 models evaluate actively used lane number (AUL_N) variable, which has a significant and negative effect on capacity. This finding contributes to the objective (lane-based capacity estimation) of the present study.

- It can be concluded that drivers in both examined cities demonstrate similar driving behaviour at intersections. This means that collecting the data from different cities would not have a great and significance effect, since drivers in both cities demonstrate similar driver characteristics (homogeneous driver distribution)
- The average vehicle number in queue (N_V) per lane at the beginning of green time does not have a significant effect on the capacity for ALLCEM-1 and ALLCEM-2 models either. This finding implies that the number of vehicles in the queues at intersection legs does not have any effect on capacity and considering the number of actively used lanes is more efficient than counting vehicles in the queues.

All findings clearly show that two different methods can be used as effective modelling methods for lane-based capacity calculation. Therefore, the use of OLS regression and ABC algorithm can be suggested as best-fit models to explain the relationship between lane capacity and different country-specific parameters. Hence, an attempt to suggest more reasonable estimation models was made by evaluating all local conditions with the aim to understand how lane capacity can change along various parameters depending on roads, traffics and driver behaviours in developing countries. The developed models may make important contribution in the design phase of the signalized intersections and thus can be of great use for the road authorities. As known from the previous studies, many researchers have focused on current capacity models in the developed countries. At the same time, different lane numbers, irregular road widths, arbitrary and undisciplined lane utilization, failure to obey distance rules, and illegal utilisation of the emergency lane are extremely common in the approach legs of intersections in many undeveloped and developing countries. For this reason, the negative effects of all these parameters on lane, leg and intersection capacity should be investigated and modelled by using different statistical, machine learning and metaheuristic algorithm methods considering extended parameters and data to develop original capacity estimation models.

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