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Development of PCU on Egyptian Roads

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Abstract: Traffic has increased rapidly in recent years, causing road congestion. Traffic volume information is crucial for designing, analyzing, and planning roadway network systems. Therefore, there must be a metric for assessing traffic flow rate or volume, where all different types of vehicles in mixed traffic volume are collected or brought to only one unit, namely PCU. As a result, the passenger car unit is an essential tool in transportation and highway engineering. There is a lack of studies of passenger car equivalents according to traffic conditions and various factors in Egypt. The main objective of this paper is to determine passenger car unit (PCU) values for varied vehicle types under heterogeneous traffic conditions on Egyptian highways and intercity roads. By analyzing the impact of traffic volume, speed, vehicle dimensions, and road characteristics, the research seeks to enhance traffic modeling and planning efforts. The speed-area/Chandra method will be employed to estimate PCU values. Required data were gathered from three main highways: Cairo-Alexandria Agriculture Road, Shubra-Banha Al-Hur axis, and Western Desert Road. The results show that the PCU values for various vehicle types across a wide range of traffic volume and highway conditions vary significantly due to vehicle types, traffic volume levels, and roadway characteristics.

Keywords: traffic volume; PCU; Mixed traffic; roadway characteristics.

1. Introduction

Rapid growth in road traffic has led to road congestion in Egypt, prompting the establishment of major projects like roads and bridges. Therefore, traffic volume and roadway capacity data are critical data points for roadway system planning, analysis, design, and operation,[1], [2], [3], [4], [5]. In most developed countries, highway capacity values and speed-flow relationships used for planning, design, and operation refer to homogeneous traffic conditions comprising vehicles with more or less uniform static and dynamic characteristics [1], [2], [6], [7], [8]. However, the traffic scenario in developing countries like India and Egypt differs significantly from the conditions of developed countries [9]. Egypt's road traffic is diverse, featuring vehicles of varying physical dimensions, weights, and dynamics, including non-standard or non-conventional vehicles, which can cause abnormal traffic behavior [2], [10]. Understanding traffic flow characteristics and vehicle interaction is crucial for highway capacity, service level analysis, and effective traffic regulation and control measures [11], [12]. The numerous vehicle types can be divided into the following categories based on the heterogeneous/mixed traffic on Egyptian roads: 1) buses; 2) trucks; 3) light commercial vehicles comprising large vans and small trucks; 4) cars (including jeeps and small vans); 5) motorized three-wheelers, which include three-wheel motorized vehicles to carry passengers and three-wheel motorized vehicles to carry small quantities of goods; 6) motorized two-wheelers, such as motorcycles, scooters, and mopeds; 7 (bicycles); 8 (tricycles for transporting passengers or small quantities of goods); and 9 (animal-drawn vehicles)[2], [7], [13], [14], [15]. These motorized and nonmotorized vehicles share the same road space without physical separation. These vehicles' speeds range from 5 to more than 100 km/h. Vehicles find it hard to follow traffic lanes due to the vast differences in physical dimensions and speeds. As a result, for maneuvering, they tend to take any lateral position along the width of the roadway, depending on available space. That causes "non-lane discipline." Allowing different types of vehicles with varying static and dynamic characteristics to mix and move on the same roadway facility can result in varying longitudinal and transverse distributions [2], [16], [17], [18]. Under previous traffic conditions, expressing traffic volume as the number of vehicles passing a given section of road per unit of time, as defined in HCM, is inappropriate. So, a more appropriate basis must be employed. Here, the importance of converting different vehicles into an equivalent vehicle unit becomes apparent [2]. The problem of measuring the volume of such diverse traffic has been solved by converting various types of vehicles into equivalent passenger cars and expressing the volume in terms of passenger car units (PCU) per hour [1]. The PCU is the universally accepted unit of measurement for traffic volume, and the value is derived using the passenger car as the "standard vehicle [1], [2], [19], [20]. As a result, estimating "PCU" values of different vehicle categories at various traffic volume levels is necessary for planning, design, and operational analysis of roadway facilities, in addition to regulation and control of traffic. The PCU values can be employed to analyze capacity, design signals, manage traffic, calculate saturation flow rates, and create traffic flow models [21]. Highway capacity is significant data for road system planning and operation, so professional organizations in various countries have developed guidelines for estimating highway capacity for distinct types of roads [22]. Unfortunately, the capacity estimates given in these manuals are based on constant PCU values for different vehicle types and only apply to level roads [14], [23]. Even on level roads, the PCU value of a vehicle category may not be constant, as it may vary depending on a variety of factors related to the roadway and traffic conditions other than vehicle factors. Hence, for accurate estimation of PCU values, it is necessary to study, at the speed level, the influence of roadway and traffic characteristics on vehicular movement. This paper investigates the effect of variations in traffic volume, speed, projected vehicle area, and changes in road characteristics (such as the number of lanes, width, and grade, for example) on vehicle PCU values." The main aim of the research work presented here is to estimate PCU values of various vehicle categories under the heterogeneous-mixed traffic conditions prevalent on Egypt's highways and intercity roads. This model employs data on traffic flow characteristics (such as free speed, traffic composition, for instance), vehicle projected area, and changes in road characteristics (such as number of lanes, width, grade, and more.). This model is then used to compute "PCU" values for various types of vehicles in mixed traffic conditions. The effect of variation in traffic volume, change in road characteristics, and vehicle size on PCU value is investigated by calculating PCU values for various types of vehicles at different ranges of traffic volume levels. Finally, the PCU values obtained by current studies are compared to the HCM to see if they vary.

2.LITERATURE REVIEW

Estimation of Passenger Car Unit (PCU) values has been a subject of interest in transportation engineering. So, various approaches were employed to estimate PCU or passenger car equivalent PCE values of vehicles [1]. For example, the Highway Capacity Manual, TRRL, Indonesian Highway Capacity Manual, and Indian Roads Congress provide many definitions of PCU based on various conditions and capacity impacts [2]. Professional organizations in many countries have tried to establish guidelines for determining road capacity values for different types of roads [2]. Unfortunately, they were all based on fixed and known PCU values for a specified number of vehicles on flat roads and under homogeneous traffic [3], [4], [5]. Moreover, previous studies have focused on estimating PCU values employing various parameters like delay, speed, density, headway, and queue discharge. All these studies, however, are mainly related to the estimation of PCE for heavy vehicles (trucks and buses) under homogeneous traffic conditions; hence, the results of these studies do not apply to Indian conditions (and the same for Egyptian roads). Other studies have shown that PCU values recommended by manuals from the United States and the U.K. may not be directly appropriate for capacity analysis in Asian countries like Singapore and Thailand, highlighting the need for region-specific analysis [6], [7], [8]. Traffic flow characteristics and roadway systems vary between developing and developed countries, posing challenges for traffic operations and road design. Developed countries mostly have homogeneous traffic with lane discipline, mainly consisting of cars, trucks, and other vehicles in small proportions,[9], [10]. Conversely, mixed traffic in developing countries consists of a diverse range of vehicles sharing the same road space without restriction,[11], [12]. Passenger car units (PCU) are employed as a standardized measure to transform traffic flows of various vehicle types into comparable flows comprising only passenger cars to address this challenge,[1], [13], [14]. In 1984, Justo and Tuladhar formulated mathematical models for determining PCU values for vehicles on urban roads based on empirical data in mixed traffic scenarios. Ramanayya, in 1988, estimated PCU factors for various vehicle types at different service levels, using the Western car as the unit for designing vehicles. Fan Henry, in 1990, provided estimations of PCU values across various vehicle categories under congested traffic flow conditions on the Pan Island Expressway in Singapore. In 2005, Terdsak and Charong studied the impact of motorcycles on traffic operations on arterial streets in Bangkok, Thailand. Their findings demonstrated a decreasing trend in the derived PCU for motorcycles as the proportion of motorcycles in the traffic stream increased [1], [2], [5].

The literature review indicates that studies on "PCU" estimation are generally related to homogeneous activity conditions, and the few conducted under heterogeneous conditions are not comprehensive enough to accurately replicate field conditions[15], [16]. There is limited research on this subject, particularly in Egypt. Therefore, there is a developing emphasis on examining vehicular interaction in heterogeneous activity to precisely determine PCU values for different vehicle types to deal with the inadequacies of homogeneous activity studies[17]. Also, studies have shown that incorporating factors like lateral width, longitudinal distance, speed, grade, and surrounding vehicle influence in PCU estimation models is crucial in providing realistic estimates, particularly in mixed-traffic environments[18]. Apart from these parameters, Chandra et al. (1995) developed an equation using the speed-area ratio to estimate PCUs for different vehicle types in mixed traffic conditions. Then, Based on previous studies by Chandra and Sikdar (2000), Tiwari et al. (2000), Chandra and Kumar (2003), Bains et al. (2012), Dhamaniya and Chandra (2013), Mardani et al. (2016), and Mohan and Chandra (2018), various parameters, such as density, queue discharge, headway, area occupancy, time occupancy, influence area, effective area, and travel time, were used under mixed traffic conditions[6], [12], [19]. Several other parameters, such as vehicle hours, platoon formation, volume-to-capacity (V/C) ratio, and directional split, have also been used by researchers to estimate PCUs. The speed-area ratio method is easy to construct and collect speed data [2]. This review provides an overview of various methods used to estimate PCU values for various facility types, such as midblock sections, signalized intersections, and uncontrolled intersections, under homogeneous and mixed traffic conditions. The methods involve different parameters for homogeneous traffic, such as speed, headway, density, delay, travel time, and queue discharge flow. The estimation for mixed traffic includes additional parameters, such as the proportion of different vehicle types and their respective PCU values. Several methods were employed to estimate PCU values on midblock sections for homogeneous and mixed traffic conditions, including urban and nonurban roads. Nonurban roads have fewer vehicle interactions than urban ones, making spatial headway methods and microscopic traffic simulations suitable for freeways and expressways,[1], [2]. The mean effective area" can be used to estimate PCU factors on midblock sections, as space occupancy of vehicles is influenced by their operational behavior in the traffic stream for urban roads, as suggested by Pooja et al. (2018). Also, adding space occupancy parameters can enhance accuracy. Also, on nonurban roads like highways, speed, flow rate, density, and delay are commonly used as performance measures for calculating PCUs on various highway types. Among them, the speed-area ratio method is a simple and efficient system for calculating "PCUs" for highways, allowing for the efficient collection of speed data,[2], [20], [21]. Chandra et al. (1995) introduced a method for estimating PCU using speed and area ratio, a widely used technique in mixed traffic studies, determining the impact of individual vehicles on urban road traffic streams[19], [22]. They employed speed as a primary variable to assess the relative impact of individual vehicles on urban roads, ensuring a fair depiction of overall vehicle interaction. However, it does not consider the standard definitions of PCUs. Furthermore, this method only analyzes cars' projected areas, although, in the field, vehicles are affected by a broader area than their projected area, proportional to the surrounding vehicle types. Chandra and Kumar's 2003 study revealed that the PCU value of vehicles on two-lane highways increases with the width of the road. Researchers used two variables to determine PCU values for vehicles on two-lane undivided rural roads: the 1-speed ratio of a car to the subject vehicle and the 2-space occupancy ratio of a car to the subject vehicle[2], [16], [23]. Hence, this research aims to estimate PCU values of various vehicle categories under heterogeneous traffic conditions on Egypt's highways and intercity roads, considering the impact of traffic volume, speed, projected vehicle area, and road characteristics on vehicle PCU values using the Chandra method/speed modeling.

3.METHODOLOGY

The present work suggests a methodology for studying/developing the dynamic nature of PCU values under the influence of varying traffic conditions (such as volume and composition) and geometric characteristics of the road. It explains that PCU is the interaction of a vehicle type with traffic streams to a car, which is reflected in the vehicle's speed, making speed one of the fundamental characteristics for estimating PCU factors. Several methods exist for estimating PCU factors, including the headway ratio method, which is suitable in lane-based traffic but loses credibility in non-lane-based traffic[2], [3]. HCM (1965) used speed and vehicle length to determine PCU factors for recreational and heavy vehicles[3]. In the case of mixed traffic flow, small-sized vehicles, such as two-wheelers, can move ahead of a car in the same lane, and two vehicles can travel ahead without concern for lane discipline. To address such problems, Chandra and Kumar (2003) proposed using physical area rather than vehicle length as a crucial criterion for estimating PCU factors[24]. The vehicle's physical area (length multiplied by width) indicates its maneuverability, the space it occupies on the road, and impedance against others in the traffic stream. The speed-area method suggested that the PCU value for different vehicles in mixed traffic conditions is directly proportional to the speed ratio and inversely proportional to the space occupancy ratio to the standard design vehicle as given by Eq. (1) proposed by Chandra and Kumar (2003):

$$PCU = \frac{V_c/V_i}{A_c/A_i} \quad (1)$$

Where V_c= speed of passenger car (m/s); V_i= speed of vehicle type i (m/s); A_c= projected rectangular area of passenger car (m2); and A_i= projected rectangular area of vehicle type i on the road (m2).

The present study collected data at several sections of the following highways: Cairo-Alexandria Agricultural Road, Shubra-Banha Axis Road, and Upper Egypt West Road, multi-lane roads in different parts of Egypt. Data collection aimed to get information on traffic volume, vehicle composition, and speed of various types of vehicles, along with the road's geometric characteristics. Collecting this information went through two attempts/methods. The first attempt was to gather the data manually since we lacked automatic traffic detectors, counters, or other cutting-edge equipment. So, a video recording technique was used during data collection time to collect the traffic data for vehicles and to cover the total trap length with a stopwatch to determine the time to cross the trap length in different sections with different grades. To calculate the different speeds of a vehicle passing through the section, the team tried to measure the time taken to cover a distance of 60-100 m. Also, the research team tried to collect data on the variant grades of the roads by using surveying devices and then obtaining the average speeds of this vehicle during each section and on a specific grade. Unfortunately, acquiring this data on such a massive scale was both challenging and expensive, in addition to the availability of several hurdles and security measures that made data collection extremely difficult. Therefore, the second attempt was undertaken, which involved collecting data from massive and reliable sources such as the Egyptian Ministry of Transport and Roads and its affiliated bodies such as the General Authority for Roads and Bridges, the National Institute of Transport, and some companies that have an enormous amount of various data required more precisely as a result of the massive available capabilities and advanced technology. The collected data obtained were traffic volume values, traffic composition (percentage of each vehicle in the traffic volume), all road data with geometric drawings (including the design of the road and its slopes), speed data, and data on the average dimensions of each class of vehicles.

4.DATA COLLECTION

4.1Traffic data:

The Cairo-Alexandria Agricultural Road, Shubra-Banha Road, and Upper Egypt Road were subjected to preliminary capacity/volume estimates and traffic studies to determine the annual average daily traffic volume (AADT), traffic flow composition, and speed of different vehicle types on the selected road sections. The proportion of vehicles in a traffic stream is crucial for the geometric and structural design. Analysis of traffic composition provides insight into the proportion of various vehicle types. As a result, understanding the traffic composition of different sections is critical. The studies of traffic composition require obtaining realistic data about the numbers and types of vehicles passing over different hours, which is the basis for calculating the passenger car unit values to identify the impact of various vehicle types on traffic flow characteristics. Table 1 presents the annual average daily traffic volume (AADT) and traffic flow composition of the sites under study.

TABLE 1. (A.A.D.T) & percentage composition of understudy Routes

Site No.	AADT (for both directions)	Percentage composition of vehicles				
		CAR	BUS	2W	LCV	HV
1	122456	57.26%	14.43%	0.20%	21.54%	6.57%
2	48149	71.63%	14.06%	0.57%	5.14%	8.60%
3	8284	55.00%	17.59%	0.07%	8.43%	18.91%

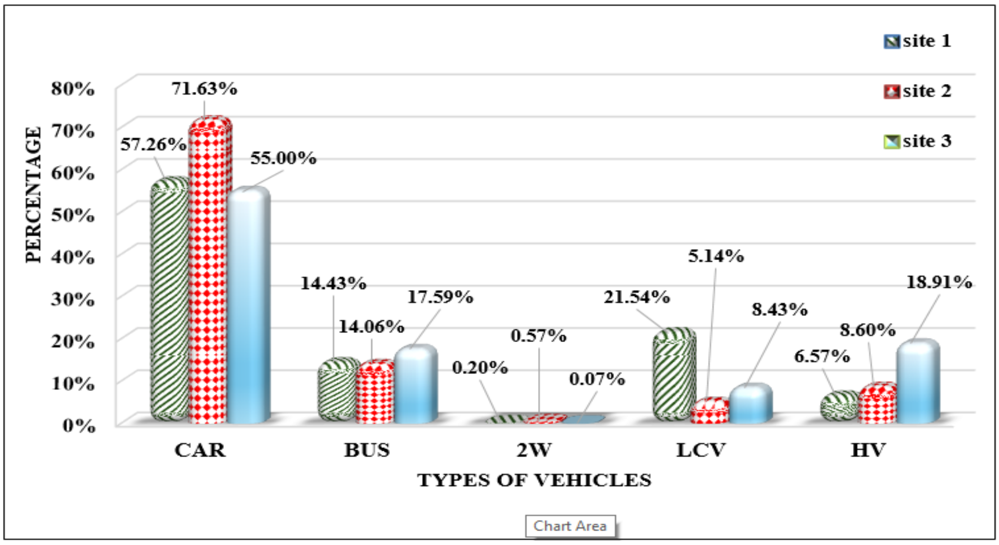

Fig1. (A.A.D.T) & percentage composition of understudy Routes

TABLE 2. Geometric Characteristics for the Sites Under Study

Site No.	**Route (station/codes)**	**Location (Road Name)**	**Direction**	**Route length (Km)**	**Width (m)**		**lanes**	
					carriageway	**Medians / Shoulders**	**Number Of Lanes**	**Lane Width**
1	(SHB-BNH), (10)	Cairo-Alexandria Agricultural Road	Cairo / Qaliubia (SHB-BNH)	46	24	2	6	3.5
2	CAI / BNHA, (190)	Shubra-Banha Axis Road	CAI / BNHA	40	36	4	8	4.5
3	(GZA-SUF), E0721	Upper Egypt West Road	Giza / Beni Suef (GZA-SUF)	184	45	16	11	4

TABLE 3. Vehicle Categories and Their Average Dimensions

Category of vehicle	**Average**		**Projected area on ground (m2)**	***Ac/Ai***
	Length	**Width**		
cars	5.79	2.13	12.33	1.00
BUSES	12.46	2.60	32.33	0.38
2W	1.89	0.75	1.40	8.78
LCV	10.58	2.44	25.80	0.48
HV	17.92	2.60	46.51	0.27

4.2Geometric data of the study areas

A suitable method to acquire these geometry data was necessary due to the unavailability of as-built drawings of the selected section of the road at the beginning. So, the first attempt was to measure road geometry characteristics in the field, including carriageway width and median width.

As a second strategy, the research team resorted to obtaining road characteristics data from the General Authority for

Roads and Bridges, as previously discussed. Geometric characteristics included the road length, the carriageway width, the number of lanes, and the pavement width. Table 2 summarizes the road geometry characteristics of the sites under study.

4.3Vehicle Categories and Their Average Dimensions

The study categorized mixed traffic on specified roads into five categories:

1. All passenger car types and taxis (PC)
2. All types of buses (Bus)
3. bikes and motorized two-wheelers (2W)
4. Minibuses and all other light commercial vehicle types (LCV)
5. All (single-double-multi) unit trucks, construction equipment, trailer trucks, and all types of heavy vehicles (HV).

The average dimensions of each vehicle category were measured either by actual field measurements, from "Egyptian Code for the Design and Implementation of Urban and Land Road Works," from other research, or the data available on manufacturer websites. Table 3 summarizes the geometric characteristics of each vehicle category.

5.DATA ANAlYSIS & RESULTS

5.1Speed Distributions

The Ministry of Transportation and the General Traffic Department) from highways over several years to analyze the effect of grades on free-flow speed. They developed a process to improve data quality by detecting and labeling abnormal speeds and collecting data under specific conditions to avoid interference from weather, holidays, and peak traffic hours. Also, road grades are measured by the ratio of vertical rise (Δh) and horizontal run distance (d), with a positive uphill grade (+) and a negative downhill grade (-). The freeway grade information is currently unavailable to the public. The research team sourced information about the grades of the selected road gradients/sections from the Ministry of Transport's database and engineering drawings. Tables 4,5,6 provide a summary of all these data.

TABLE 4. Vehicles' speed at different grades for site 1

Gradient	Average Speed (km/h)				
	Cars	Buses	2W	LCV	HCV
-3.00%	74.83	59.64	65.40	62.08	55.90
-2.00%	74.30	58.43	64.18	60.49	54.50
-1.50%	72.82	56.50	61.86	59.51	53.16
-1.00%	70.97	54.04	63.01	58.74	50.89
0.00%	69.39	52.51	61.08	56.86	49.52
1.00%	66.14	49.88	58.64	54.43	46.88
1.50%	63.39	46.56	57.10	52.15	44.19
2.00%	62.57	45.02	55.18	50.00	42.90
3.00%	61.78	43.95	54.13	49.35	40.99

TABLE 5. Vehicles' speed at different grades for site 2

Gradient	Average Speed (km/h)				
	Cars	Buses	2W	LCV	HCV
-3.00%	88.98	67.70	78.77	73.69	63.69
-2.00%	87.50	65.86	76.96	71.16	62.37
-1.50%	85.92	64.12	76.00	70.08	61.00
-1.00%	84.80	62.78	75.30	68.16	59.75
0.00%	82.58	60.41	72.59	66.33	57.91
1.00%	79.02	57.80	70.26	63.57	56.37
1.50%	78.18	56.27	67.45	61.91	54.90
2.00%	75.26	54.08	63.06	59.17	52.67
3.00%	73.12	52.18	60.40	57.40	50.96

TABLE 6. Vehicles' speed at different grades for site 3

Gradient	Average Speed (km/h)				
	Cars	Buses	2W	LCV	HCV
-3.00%	96.38	79.61	93.89	89.65	74.27
-2.00%	94.67	76.89	91.82	86.80	72.50
-1.50%	94.27	76.09	90.80	85.50	71.37
-1.00%	92.75	74.39	90.01	82.44	70.21
0.00%	89.39	71.59	87.22	79.25	67.60
1.00%	85.41	68.02	83.25	75.31	64.30
1.50%	82.92	65.30	81.02	72.57	62.15
2.00%	81.59	64.19	79.29	69.33	60.98
3.00%	80.43	62.03	76.62	68.21	59.55

TABLE 7. PCU values of different types of vehicles for site 1

Gradient	$\mathbf{PCU} = \frac{V_c/V_i}{A_c/A_i}$				
	Cars	Buses	2W	LCV	HCV
-3.00%	1.00	3.29	0.13	2.52	5.05
-2.00%	1.00	3.33	0.13	2.57	5.14
-1.50%	1.00	3.38	0.13	2.56	5.17
-1.00%	1.00	3.44	0.13	2.53	5.26
0.00%	1.00	3.46	0.13	2.55	5.28
1.00%	1.00	3.48	0.13	2.54	5.32
1.50%	1.00	3.57	0.13	2.54	5.41
2.00%	1.00	3.64	0.13	2.62	5.50
3.00%	1.00	3.69	0.13	2.62	5.68

TABLE 8. PCU values of different types of vehicles for site 2.

Gradient	$\mathbf{PCU} = \frac{\mathrm{V_c}/\mathrm{V_i}}{\mathrm{A_c}/\mathrm{A_i}}$				
	Cars	BUSES	2W	LCV	HV
-3.00%	1.00	3.45	0.13	2.53	5.27
-2.00%	1.00	3.48	0.13	2.57	5.29
-1.50%	1.00	3.51	0.13	2.57	5.31
-1.00%	1.00	3.54	0.13	2.60	5.35
0.00%	1.00	3.58	0.13	2.60	5.38
1.00%	1.00	3.58	0.13	2.60	5.29
1.50%	1.00	3.64	0.13	2.64	5.37
2.00%	1.00	3.65	0.14	2.66	5.39
3.00%	1.00	3.67	0.14	2.67	5.41

TABLE 9. PCU values of different types of vehicles for site 3

Gradient	$PCU = x = \frac{V_c/V_i}{A_c/A_i}$				
	Cars	BUSES	2W	LCV	HV
-3.00%	1.00	3.17	0.12	2.25	4.89
-2.00%	1.00	3.23	0.12	2.28	4.92
-1.50%	1.00	3.25	0.12	2.31	4.98
-1.00%	1.00	3.27	0.12	2.35	4.98
0.00%	1.00	3.27	0.12	2.36	4.99
1.00%	1.00	3.29	0.12	2.37	5.01
1.50%	1.00	3.33	0.12	2.39	5.03
2.00%	1.00	3.33	0.12	2.46	5.05
3.00%	1.00	3.40	0.12	2.47	5.09

5.3PCU Variation with Respective Speed

The increasing motor vehicle population has led to a growth in road traffic, with speed, density, and volume being the most crucial components. Traffic engineers utilize relationships to plan, design, and implement traffic engineering measures on roads or highways, with the performance of these networks largely influenced by traffic capacity, speed, and volume.

The study analyzes the average spot speed of all vehicles and finds that speed varies with gradients. As the gradient increases, the speed decreases, even though the lane width is the same. Based on Satish Chandra's method, which reveals that PCU values for different types of vehicles vary at different gradients. Figures 2, 4, and 6 summarize the relation between PCU values for each vehicle type and respective speeds on ascending grades for sites 1, 2, and 3, respectively. Figures 3, 5, and 7 summarize the relation between PCU values for each vehicle type and respective speeds on descending grades for sites 1, 2, and 3, respectively.

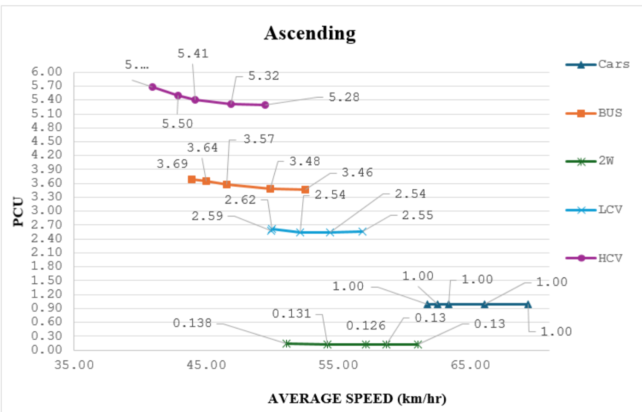

Fig 2. PCU variation on ascending gradients for Site 1

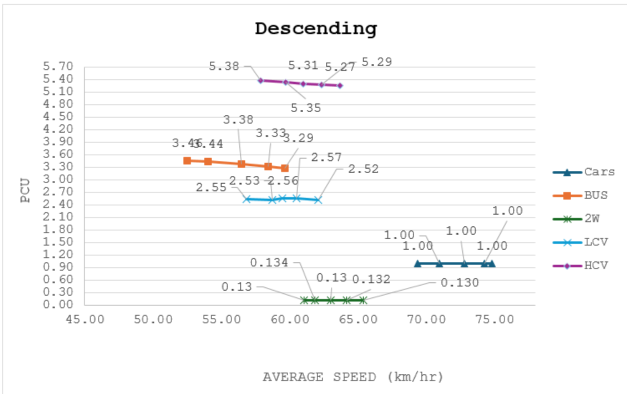

Fig 3. PCU variation on descending gradients for Site 1

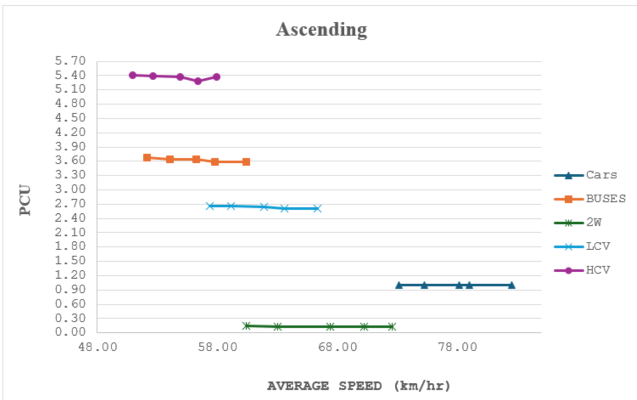

Fig 4. PCU variation on ascending gradients for Site 2

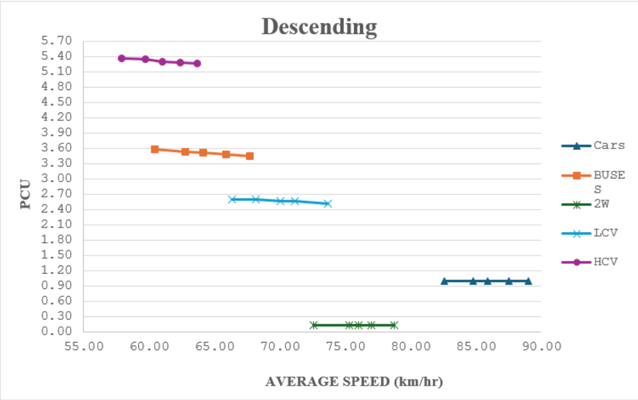

Fig 5. PCU variation on descending gradients for Site 2

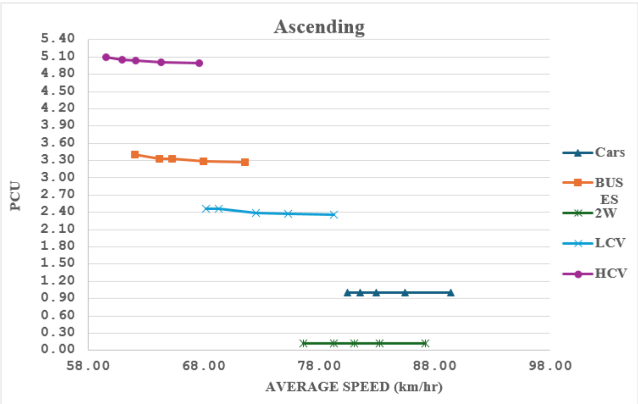

Fig 6. PCU variation on ascending gradients for Site 3

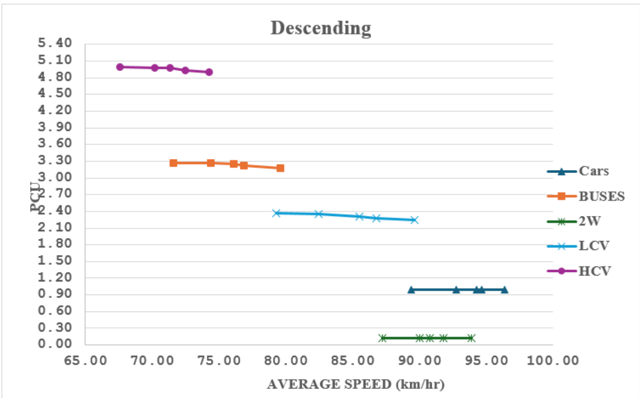

Fig 7. PCU variation on descending gradients for Site 3

5.4 Results

Furthermore, a deeper analysis of the preceding tables and charts reveals the following:

- In the case of an ascending grade (+), the value of PCU was increased. Conversely, for a descending grade (-), the value of the PCU for each type of vehicle decreased. Except for two-wheeled vehicles, which showed a unique pattern, they maintained relatively constant PCU values regardless of grade differences.
- In the case of a grade equal to zero, we find that the PCU values are higher than those in the case of descending grade and lower than those in ascending grade.
- Heavy vehicles exhibit the highest PCU values, followed by buses, light commercial vehicles, cars, and two-wheelers, regardless of the direction of traffic flow (ascending or descending) across all three sites.

- For sites/routes with zero grade:
    - PCU values were highest at Site 2, followed by Site 1, and lowest at Site 3.
    - Across all sites, heavy vehicles exhibited the highest PCU values, followed by buses, light commercial vehicles, and two-wheeled vehicles (2W).
    - Notably, 2W vehicles maintained relatively constant PCU values across all sites, with a slight decrease observed at Site 3.

- For ascending grades, as depicted in Figures 2, 4, and 6:
    - PCU values for heavy vehicles were highest in Site 1, followed by Site 2 and Site 3, with values decreasing as the ascending grade increased.
    - Buses, similarly, showed the highest PCU values in "Site 1," followed by "Site 2," and then "Site 3.". Notably, its PCU value at (+3%) grade in Site 1 exceeds that of Site 2.
    - Light commercial vehicles had the highest PCU values in Site 2, followed by Site 1 and Site 3, with relatively small differences between the sites.
    - Two-wheelers, 2W, maintained nearly constant PCU values across all sites.
    - Lastly, for ascending grades, as shown in Figures 2 and 4, Site 2 generally displayed the highest PCU values for all vehicle types, except heavy vehicles, which had higher PCU values in Site 1.

- For descending grades, as depicted in Figures 3, 5, and 7:
    - Heavy vehicles exhibited higher PCU values in "Site 1" than in "Site 3" but lower values than "Site 2.".
    - Similarly, buses had the highest PCU values in Site 2, followed by Site 1, and the lowest in Site 3.
    - Light commercial vehicles had relatively similar PCU values across the sites, with Site 2 showing slightly higher values than "Site 1" and both exceeding Site 3.
    - As for the values of 2W, they were almost all equal as they remained constant in the three sites.

- A comparison of Figures 3 and 5 reveals that, despite Site 1 having a traffic density 2.5 times higher than Site 2, the PCU values in Site 2 were(approximately 2.25%) higher than those in Site 1.
- Furthermore, comparing Sites 2 and 3 (Figures 5 and 7) and Sites 1 and 3 (Figures 3 and 7) reveals a decrease in PCU values at Site 3, with a 6.5% decrease compared to Site 2 and approximately 5.4% decrease compared to Site 1, respectively, suggesting substantial variations in traffic performance across these sites.

The observed relationship between grade and PCU values, as well as the hierarchy of PCU values among different vehicle types, can be attributed to the interplay of vehicle dimensions, operating speeds, traffic conditions, and road characteristics on these factors. According to Chandra's method, equation (1), PCU is directly proportional to (Vc/Vi) and inversely proportional to (Ac/Ai).

Regarding the impact of grade:

- Ascending Grades**:** Increased resistance to motion on ascending grades leads to reduced vehicle speeds, particularly for heavy vehicles due to their significant mass and large projected area. This results in higher PCU values for heavy vehicles on steeper grades. Conversely, lighter vehicles, with smaller projected areas and lower mass, are less affected by grade changes, leading to relatively lower PCU values.
- Descending Grades: While descending grades generally lead to increased speeds, the impact on PCU values varies by vehicle type. Heavy vehicles, despite gaining speed, still maintain a significant speed difference compared to passenger cars due to their size and weight. This contributes to higher PCU values for heavy vehicles, even on descending grades.
- For sections with zero grades, the PCU values observed were intermediate between those recorded on ascending and descending grades. With no gravitational forces acting in either direction, they eliminate the influence of slope-induced resistance or acceleration, thereby no impact of grade on vehicle speed and, consequently, PCU values. Consequently, other factors, such as traffic volume, road geometry, and environmental conditions, play a more significant role in determining PCU values on flat road sections.

Regarding the impact of traffic density and road characteristics:

- Higher Traffic Density: In sites with higher traffic density, such as Site 1, increased congestion and reduced traffic flow lead to lower vehicle speeds, particularly for larger vehicles. This results in higher PCU values, as the speed difference between passenger cars and other vehicles increases.
- Road Characteristics:
  - Sites with wider roads, more lanes, and less congested conditions, like Site 3, allow for higher vehicle speeds. This reduced speed differential between vehicle types leads to lower PCU values.
  - Despite Site 1 exhibiting significantly higher traffic density, Site 2 demonstrated higher PCU values, whether zero or descending grade. This disparity can be attributed to the superior road infrastructure of Site 2, characterized by wider roads and multiple lanes. These favorable conditions allowed for higher vehicle speeds, particularly for passenger cars, increasing the speed differential between passenger cars and other vehicles. Consequently, the PCU values for heavy vehicles in Site 2 increased. In contrast, Site 1's higher traffic density and narrower roads constrained speeds for all types of vehicles, including cars, leading to reduced speed differentials and lower PCU values.

In summary, the combination of vehicle dimensions, operating speeds, grade, and road characteristics significantly influences PCU values. Larger, heavier vehicles, especially on ascending grades and in congested conditions, exhibit higher PCU values. Conversely, smaller, lighter vehicles, particularly in less congested areas with favorable road conditions, tend to have lower PCU values.

6.CONCLUSIONS

This study delves into the pressing issue of traffic congestion in Egypt, exacerbated by rapid growth in recent years. To address this challenge, a comprehensive analysis of traffic flow characteristics and vehicle interactions is essential. The research focuses on estimating dynamic passenger car unit (PCU) values under diverse traffic conditions and road geometries. By employing the speed-area method, the study offers a robust approach to understanding the impact of factors such as vehicle type, traffic volume, speed, and road characteristics on traffic flow. Data was meticulously collected from three major Egyptian highways, enabling a detailed analysis of speed distributions and the determination of PCU values. The results reveal significant variations in PCU values across different vehicle types and traffic conditions. Notably, heavy vehicles exhibit the highest PCU values, while two-wheelers have the lowest. Furthermore, the study highlights the influence of road geometry, particularly ascending and descending grades, on PCU values. The findings of this research provide valuable insights for traffic engineers and policymakers in Egypt. By understanding the complex interplay between vehicle types, traffic flow, and road infrastructure, it is possible to develop effective traffic management strategies, improve road capacity, and enhance overall traffic efficiency. The study's methodology and results can be applied to other developing countries with similar traffic challenges.

REFERENCE

[1] V. T. Arasan and S. S. Arkatkar, "Microsimulation Study of Effect of Volume and Road Width on PCU of Vehicles under Heterogeneous Traffic," *JOURNAL OF TRANSPORTATION ENGINEERING © ASCE*, vol. 136, no. 12, pp. 1110–1119, Dec. 2010, doi: 10.1061/ASCETE.1943-5436.0000176.

[2] P. Raj, K. Sivagnanasundaram, G. Asaithambi, and A. U. Ravi Shankar, "Review of Methods for Estimation of Passenger Car Unit Values of Vehicles," *J Transp Eng A Syst*, vol. 145, no. 6, Jun. 2019, doi: 10.1061/jtepbs.0000234.

[3] M. M. Nokandeh, I. Ghosh, A. M. Asce, and S. Chandra, "Determination of Passenger-Car Units on Two-Lane Intercity Highways under Heterogeneous Traffic Conditions," 2015, doi: 10.1061/(ASCE)TE.1943-5436.

[4] J. T. S. Al-Obaedi, "Estimation of Passenger Car Equivalents for Basic Freeway Sections at Different Traffic Conditions," *World Journal of Engineering and Technology*, vol. 04, no. 02, pp. 153–159, Apr. 2016, doi: 10.4236/wjet.2016.42013.

[5] M. Sharma and S. Biswas, "Estimation of Passenger Car Unit on urban roads: A literature review," Sep. 01, 2021, *Elsevier B.V.* doi: 10.1016/j.ijtst.2020.07.002.

[6] Z. (Sean) Qian, J. Li, X. Li, M. Zhang, and H. Wang, "Modeling heterogeneous traffic flow: A pragmatic approach," *Transportation Research Part B: Methodological*, vol. 99, pp. 183–204, May 2017, doi: 10.1016/J.TRB.2017.01.011.

[7] S. Mondal, S. Chakraborty, S. K. Roy, and A. Gupta, "Estimation of passenger car unit for heterogeneous traffic stream of urban arterials: case study of Kolkata," *Transportation Letters*, vol. 15, no. 10, pp. 1276–1288, Nov. 2023, doi: 10.1080/19427867.2017.1293313.

[8] S. I. Khan and P. Maini, "Modeling Heterogeneous Traffic Flow," *Transp Res Rec*, vol. 1678, no. 1, pp. 234–241, Jan. 1999, doi: https://doi.org/10.3141/167.

[9] E. Macioszek, "The passenger car equivalent factors for heavy vehicles on turbo roundabouts," *Front Built Environ*, vol. 5, Apr. 2019, doi: 10.3389/fbuil.2019.00068.

[10] O. Giuffrè, A. Granà, T. Giuffrè, M. L. Tumminello, and F. Acuto, "Passenger car equivalents for heavy vehicles at roundabouts. A synthesis review," *Front Built Environ*, vol. 5, Jun. 2019, doi: 10.3389/fbuil.2019.00080.

[11] A. Ahmed, M. R. Mehdi, D. Ngoduy, and M. Abbas, "Evaluation of accuracy of advanced traveler information and commuter behavior in a developing country," *Travel Behav Soc*, vol. 15, pp. 63–73, Apr. 2019, doi: 10.1016/j.tbs.2018.12.003.

[12] G. Asaithambi, H. S. Mourie, and R. Sivanandan, "Passenger car unit estimation at signalized intersection for non-lane based mixed traffic using microscopic simulation model," *Periodica Polytechnica Transportation Engineering*, vol. 45, no. 1, pp. 12–20, Dec. 2017, doi: 10.3311/PPtr.8986.

[13] B. P. Saha, D. Q. S Hossain, H. M. I Mahmud, and Z. Islam, "PASSENGER CAR EQUIVALENT (PCE) OF THROUGH VEHICLES AT SIGNALIZED INTERSECTIONS IN DHAKA METROPOLITAN CITY," 2009.

[14] H. Liu, M. O. Rodgers, and R. Guensler, "Impact of r oad grade on vehicle speed-acceleration distribution, emissions and dispersion modeling on freeways," *Transp Res D Transp Environ*, vol. 69, pp. 107–122, Apr. 2019, doi: 10.1016/j.trd.2019.01.028.

[15] R. Pajecki, F. Ahmed, X. Qu, X. Zheng, Y. Yang, and S. Easa, "Estimating passenger car equivalent of heavy vehicles at roundabout entry using micro-traffic simulation," *Front Built Environ*, vol. 5, May 2019, doi: 10.3389/fbuil.2019.00077.

[16] X. Chen, Z. Li, Y. Wang, Z. Cui, C. Shi, and H. Wu, "Evaluating the impacts of grades on vehicular speeds on interstate highways," *PLoS One*, vol. 12, no. 9, Sep. 2017, doi: 10.1371/journal.pone.0184142.

[17] C.-J. Lan and M. Menendez, "Truck Speed Profile Models for Critical Length of Grade," *JOURNAL OF TRANSPORTATION ENGINEERING © ASCE*, vol. 129, pp. 408–419, Aug. 2003, doi: 10.1061/ASCE0733-947X2003129:4408.

[18] M. SUBOTIĆ and V. TUBIĆ, "CAR EQUIVALENTS DEPENDENCE ON THE LONGITUDINAL ROAD GRADIENT ON TWO-LANE ROADS IN BOSNIA AND HERZEGOVINA," *Promet – Traffic&Transportation*, vol. 29, no. 4, pp. 401–409, Sep. 2017, doi: https://doi.org/10.7307/ptt.v29i4.2226.

[19] A. Shalkamy, D. Said, L. Radwan, T. Engineer, and D. Al Handasah Shair, "Influence of Carriageway Width and Horizontal Curve Radius on Passenger Car Unit Values of Two-lane Two-way Rural Roads," Online, 2015. [Online]. Available: https://www.researchgate.net/publication/311793705

[20] N. Y. Cao and K. Sano, "Estimating Capacity and Motorcycle Equivalent Units on Urban Roads in Hanoi, Vietnam," *J Transp Eng*, vol. 138, no. 6, pp. 776–785, doi: 10.1061/(ASCE)TE.1943-5436.0000382.

[21] S. Mondal, S. Chakraborty, S. K. Roy, and A. Gupta, "Estimation of passenger car unit for heterogeneous traffic stream of urban arterials: case study of Kolkata," *Transportation Letters*, vol. 15, no. 10, pp. 1276–1288, 2023, doi: 10.1080/19427867.2017.1293313.

[22] P. K. P MTech Student and V. B. G Asst Professor, "Study on Effect of Gradients on PCU and Capacity Factor for Undivided Two Lane National Highway (NH-209)," *International Journal of Engineering Research & Technology (IJERT)*, vol. 6, no. 8, pp. 291–295, Aug. 2017, doi: IJERTV6IS080130.

[23] A. R. Khanorkar, S. D. Ghodmare, and B. V Khode, "Impact of Lane Width of Road on Passenger Car Unit Capacity under Mix Traffic Condition in Cities on Congested Highways," 2014. [Online]. Available: www.ijera.com

[24] N. M. Mardani, S. Chandra, and I. Ghosh, "Passenger car unit of vehicles on undivided intercity roads in India," in *Procedia Computer Science*, Elsevier B.V., 2015, pp. 926–931. doi: 10.1016/j.procs.2015.05.167.