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The Influences of Macroscopic Modeling of Traffic Dynamics in Urban Road Segments Considering Side Friction Influences: A Case Study

Edwin Mararo Lekariap, Zachary Gariy, Timothy Nyomboi

***Abstract:** Urban road networks are essential arteries of modern cities, facilitating the movement of people and goods. However, efficient traffic flow management in urban areas remains a critical challenge, often compounded by factors like side friction. This research article presents a comprehensive macroscopic modeling approach to understand and incorporate the effects of side friction on traffic flow in the context of Nakuru City, Kenya. Nakuru City, like many growing urban centres, grapples with traffic congestion and associated issues, demanding innovative solutions for sustainable urban mobility. Side friction, a multifaceted factor influenced by various urban elements such as parked vehicles, pedestrian activities, and roadside infrastructure, significantly impacts traffic flow dynamics. This study employed a macroscopic modeling framework to capture the complex interplay between traffic flow and side friction in Nakuru City's road links. Through extensive data collection and analysis, coupled with advanced traffic modeling techniques, the research developed a nuanced understanding of how side friction affects traffic flow patterns.*

***Keywords:** Macroscopic modeling, Nakuru City, side friction, traffic management, urban road links, urban traffic flow.*

I. INTRODUCTION

Urbanization, a hallmark of contemporary societies, has led to rapid population growth and increased vehicular traffic in cities worldwide (Goetz, 2019) [2]. The efficient management of traffic flow in urban road networks is paramount for ensuring mobility, reducing congestion, and mitigating associated environmental and economic challenges (Zadobrischi, Cosovanu, & Dimian, 2020) [6].

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However, the intricate dynamics of urban traffic flow are influenced by a multitude of factors, among which side friction plays a pivotal role. Side friction, encompassing a range of interactions along urban road links, arises from diverse elements such as parked vehicles, pedestrian activities, and roadside infrastructure (Hidayat, Sunarjono, Awad, & Magfirona, 2019) [3]. Understanding and modeling the effects of side friction are essential for developing traffic management strategies that enhance the efficiency and safety of urban transportation systems. In this context, Nakuru City, Kenya, provides an apt case study[7].

This article is based on a comprehensive investigation, utilizing advanced macroscopic modeling techniques, to shed light on the intricate relationship between traffic flow dynamics and side friction in Nakuru's urban road links [8]. The aforementioned approach can be employed to estimate aspects that are related to traffic in urban areas (Jiang, Ma, & Zhou, 2018) [4]. By adopting a holistic approach that integrates real-world data collection, statistical analysis, and traffic modeling, the article provides a deeper understanding of the implications of side friction on traffic flow [9]. The findings of this research are poised to advance both theoretical knowledge and practical applications in the realm of urban traffic management (UN-Habitat, 2010) [5]. In bridging the gap between theory and practice, the insights obtained from this study can inform the development of tailored traffic management strategies and infrastructure planning for Nakuru City, contributing to its sustainable urban development [10].

II. RESEARCH METHODOLOGY

Fig.1: Major Road Links in Nakuru City and Its Environs

Speed limits for major arterial in Nakuru City ranged from 50 km/h to 80 km/h depending on location within the town area while for most collectors it was below 50 km/hr, and most local roads were rarely posted with any speed limits. Parking lanes were common on downtown streets, which are local streets and essentially function for accessibility [11]. Mostly, collector and local roads outside the Central Business District (CBD) were characterized by unpaved and undesignated walkways. Generally, only part of the observed network especially arterial and collector roads were suitable for this study. According to the Road Design Manual, the Nakuru-Eldoret Highway, Nakuru-Nairobi Highway, and Nakuru-Nyahururu Road were desired to have full level of access control. The level of access could also be reduced to partial control on this road due to practical reasons and financial constraints. The desirable level of access for Nakuru - Nyahururu Road, Nakuru - Kabarak Road, Nakuru - Elementaita Road, Oginga Odinga Road, Moi Road, Nakuru - Njoro Road, Nakuru - Bangladesh Road, and Nakuru - Ndundori Road was either full or partially controlled but could be reduced to the latter.

A. Data Collection

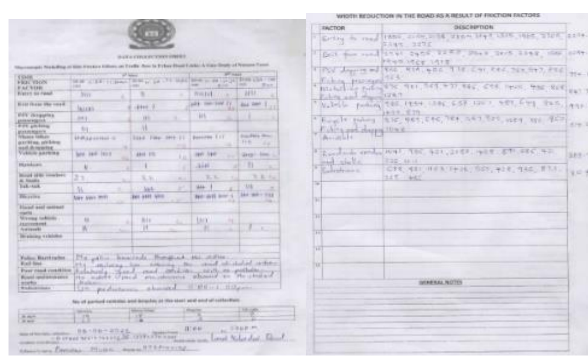
A large amount of field data was collected in order to get a true picture of the conditions on the road links in Nakuru City. The main survey (data collection) was conducted for a period of three months when the weather was favorable to collect the data. Prior to the main survey, site visits were made to all the roads in the City. The team of research assistant drove to all the 11 roads where key observations were made in identifying the main friction factors on those sections. Sites where the actual data was collected from were also identified during the survey period. The time schedule of conducting the survey on the stated roads is outlined in Table 1. A total of 66 field hours were spent in carrying out the survey on the frequency of friction factors, 168 hours in collecting data on traffic characteristics using metro count road side units, and 33 hours in surveying the impact of the friction factors on carriageway width. In determination of the frequency of friction factors, data was collected three times in a day, that is, morning (0800hrs-1000hrs), noon (1100hrs-1300hrs), and evening (1500-1700hrs). To determine the traffic characteristics, the installed roadside units collected data continuously for 7 days. The width reduction as a result of friction factors was also recorded in three sessions per day, that is, morning (0800hrs-0900hrs), noon (1200hrs-1300hrs) and evening (1600hrs-1700hrs).

Table 1: Data Collection Schedule

	Road section	Coordinate	Chainage	Friction Factor Frequency	Width Reduction Survey	Traffic Characteristics Determination	Logger Number
1	Oginga Odinga road	E: 0.290007 N: 36.072029	0 + 525	24/05/2022	24/05/2022	20/06/2022-27/06/2022	Logger 37
2	Moi road	E: 0.289785 N: 36.071698	0 + 837	25/05/2022	25/05/2022	20/06/2022-27/06/2022	Logger 38
3	PGH road	E: 0.278689 N: 36.072029	0+ 883	26/05/2022	26/05/2022	20/06/2022-27/06/2022	Logger 39
4	Nakuru – Kaptembwa road	E: 0. 291196 N: 36.053602	0+ 160	27/05/2022	27/05/2022	28/06/2022-05/07/2022	Logger 41
5	Nakuru Njoro road	E: -0.33366 N: 35.945233	16+ 408	31/05/2022	31/05/2022	28/06/2022-05/07/2022	Logger 38
6	Nakuru Kabarak road	E: -0.281478 N: 36.061158	0 + 858	02/06/2022	02/06/2022	06/07/2022-13/07/2022	Logger 41
7	Nakuru Nyahururu road	E: -0.276411 N: 36.098705	0+952	03/06/2022	03/06/2022	06/07/2022-13/07/2022	Logger 37
8	Nakuru Elementaita road	E: -0.320952 N: 36.142727	0+ 436	06/06/2022	06/06/2022	06/07/2022-13/07/2022	Logger 38
9	Nakuru Bangladesh road	E: -0.290060 N: 36.056002	0+ 95	07/06/2022	07/06/2022	28/06/2022-05/07/2022	Logger 37
10	Lanet Ndundori road	E: -0.298670 N: 36.137924	1+ 279	08/06/2022	08/06/2022	06/07/2022-13/07/2022	Logger 39
11	Eldoret Nakuru 1	E: -0.289870 N: 36.053284	1+ 236	10/06/2022	10/06/2022	18/07/2022-25/07/2022	Logger 37
12	Eldoret Nakuru 2	E: -0.289870 N: 36.053284	1+ 236	10/06/2022	10/06/2022	18/07/2022-25/07/2022	Logger 38
13	Nakuru Eldoret 1	E: -0.289870 N: 36.053284	2+ 236	10/06/2022	10/06/2022	18/07/2022-25/07/2022	Logger 39
14	Nakuru Eldoret 2	E: 0.290007 N: 36.072029	0 + 525	10/06/2022	10/06/2022	18/07/2022-25/07/2022	Logger 41

B. Site-Specific Causal Factors of Side Friction in Urban Road Links

Side friction data was recorded manually in a form that was prepared prior to the study. The form contained sections to fill the name of the road link under study, the exact coordinates of the site, time of survey, date of collection, name of surveyor and their contact details. The frequency of friction factors was counted and recorded by the surveyors manually. All data was collected within 100m length. Space was also provided to record any new friction factor and record their frequency. A sample side friction survey form is illustrated in Figure 1.



[Fig.1: Sample Side Friction Survey Form]

C. Characteristics of Traffic Flow

In order to document traffic flow characteristics, the metro count vehicle classifier road side units were installed on the road and data recorded on them (Figure 2). This helped in obtaining data on vehicle speeds, vehicle classification and their respective counts, and traffic flow among other characteristics over a long period of time. The data obtained from the classifier systems was accurate and hence this eliminated the possibility of errors that could have been made by people when collecting the data manually. The vehicles were classified into 12 classes using the ARX vehicle classification as defined by metro count. Other flow characteristics which were not recorded on the metro count classifier system were obtained during the data reduction and cleaning procedure. There were two types of sites considered in the installation of the metro count devices. One road side unit was installed for all bidirectional traffic flows in ten roads. This was as a result of low-level degeneration of data quality. There were few vehicles overtaking or moving in the wrong direction thus limiting the traffic crossing the tubes simultaneously hence the data quality obtained was relatively good. For dual carriage Nairobi-Nakuru-Eldoret highway, two road site units were installed on each section with two lanes per section. The occurrence of two vehicles crossing the tubes at the same time was high. This resulted in difficulties in discerning the actual vehicles due to the sequence of axle hits consequently produced by such simultaneous events.

[Fig.2: Installation of Metro Count Roadside Units on Site]

III. RESULTS AND DISCUSSION

A. Classification of Friction Factor Frequency Intensity

The frequency of friction factors was determined by the surveyors and enumerators in a data collection sheet. Data was collected during peak hours and an average of the frequency was done for the peak hours and classification of the intensity done on all road sections. SFF whose frequency was less than 5 events per hour were considered to have negligible impact and thus not considered for further analysis. Data on SFFs was recorded including those that had not been anticipated before, for example, slow moving driving school vans, vehicles with mechanical problems, and vehicles stopping as a result of road shows among others. Since it was not easy to know SFFs with negligible impacts, data was collected on all observed SFFs and the one with the least frequency removed during data cleaning. The peak average frequencies of the SFFs were summed up and classified in order to determine the road links with the highest effect. In most of the road links pedestrians were observed to be the most frequent SFF as shown in Table 2.

Table 2: Summary of Side Friction Factor Frequency Occurrence

Freq/Hr/100m	Entry	Exit	PSV D	PSV P	Motor Bikes	Parking	Roadside Vendors	Tuk-tuk	Bicycles	Carts	Ped	Ped Cross	Total
Bangladesh	41.83	28.67	7.17	4.33	64.00	34.00	8.00	36.50	63.83	4.00	245.83	23.67	**561.83**
Elementaita	56.33	46.17	5.50	7.50	7.50	8.50	14.00	18.50	16.33	0.33	113.17	19.50	**313.33**
Kabarak	8.33	11.50	10.33	11.67	8.83	4.67	0.00	27.00	14.00	0.17	184.83	26.00	**307.33**
Kaptembwa	21.33	15.00	3.33	0.67	22.33	15.67	27.67	5.00	54.50	0.83	688.83	61.50	**916.67**
Lanet	23.67	28.50	5.17	4.33	31.00	30.50	44.00	9.67	29.67	0.50	83.50	11.83	**302.33**
Moi	27.33	22.83	0.00	0.00	28.00	13.00	8.00	20.83	28.83	0.83	351.67	20.67	**522.00**
Njoro	19.14	9.61	5.06	6.57	5.71	10.74	1.25	40.16	3.05	4.25	114.84	13.78	**234.17**
Nyahururu	86.00	37.50	18.50	16.17	7.50	8.33	4.00	25.33	45.67	0.00	617.33	43.50	**909.83**
O. Odinga	27.00	45.00	0.00	0.00	30.83	40.83	0.00	35.50	111.83	1.00	772.00	124.67	**1,188.67**
PGH	39.00	34.50	4.50	7.17	30.67	11.00	26.00	29.00	19.83	1.17	908.17	81.00	**1,192.00**
Nkr-Eld	11.84	18.93	12.70	11.88	4.30	11.31	30.21	17.25	22.23	1.67	125.99	15.07	**283.38**
Average	32.89	27.11	6.57	6.39	21.88	17.14	14.83	24.07	37.25	1.34	382.38	40.11	**611.96**
Grand Total	**5%**	**4%**	**1%**	**1%**	**4%**	**3%**	**2%**	**4%**	**6%**	**0%**	**62%**	**7%**	

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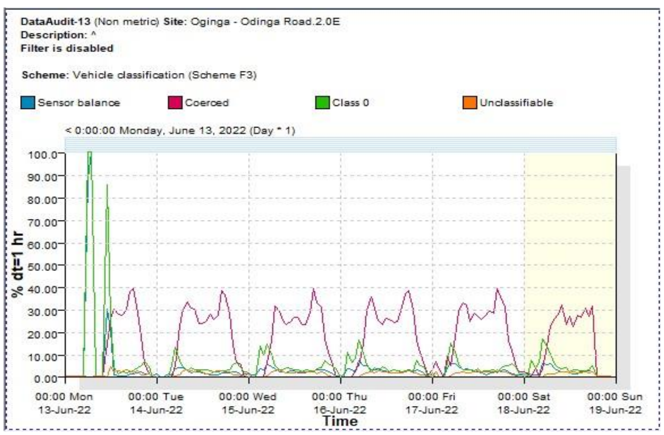
B. Traffic Flow Incorporating Effects of Side Frictions

To model traffic flow relationships between different parameters, the average speeds of traffic flow were collected from the metrocount devices for all the studied road links in Nakuru City. A sample data of Oginga Odinga Road link is as shown in Table 3.

Table 3: Sample Traffic Average Speed Data for Oginga Odinga Road Link

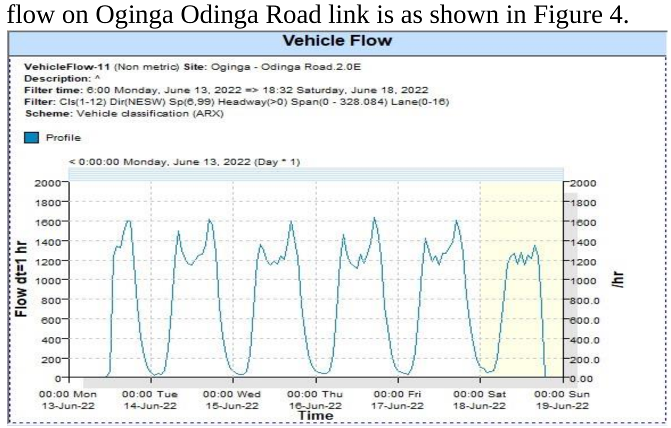
Speed (km/hr)	1	2	3	4	5	6	7	8	9	10	11	12	Total	%
10-20	4248	3256	89	68	39	173	8	14	15	52	12	10	7984	7.7
20-30	11633	19561	844	424	112	901		94	62	333	73	104	34141	32.8
30-40	19692	25168	532	489	63	1096	3	75	66	235	45	67	47531	45.7
40-50	6272	5482	44	104	18	163		13	11	11	4	1	12123	11.7
50-60	1131	634	6	14	5	17							1807	1.7
60-70	164	97	1	2		5							269	0.3
70-80	6	19		1									26	0
80-90		9		3									12	0
90-100		3	1										4	0
100-110		8											8	0
110-120		10		2									12	0
120-130				2									2	0
130-140		9		1									10	0
140-150		2											2	0
150-160		5		1									6	0
Total	43146	54263	1517	1111	237	2355	11	196	154	631	134	182	103937	
%	41.5	52.2	1.5	1.1	0.2	2.3	0	0.2	0.1	0.6	0.1	0.2		

The results in respect of event and vehicular flow on the Oginga Odinga Road link are presented in Figure 3.



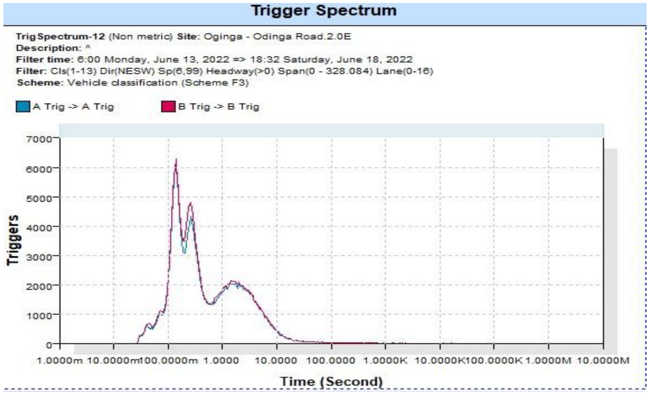
[Fig.3: Event and Vehicular Flow]

Oginga Odinga Road link was examined with regard to the event flows because it is located in the CBD of Nakuru City and features the existence of paved walkways, road side parking and no PSVs were allowed on the road link. The foregoing depict a perfect representation of streets in urban areas. The trend of events was the same during all the weekdays with peak events exhibited in the morning and evening hours. The events happening in the evening were observed to be slightly more than those taking place in the morning. During the installation of the vehicle classifier units, events of class 0 were observed to be very high. Class 0 hits are sensor hits that cannot be classified as traffic and commonly occured when the events that are fewer than two matching AB sensor hit pairs or the event only hit one sensor. This was a common occurence which was eliminated after completing the installation. The vehicle flow curve showed a similar trend as the event flows with vehicular flow showing a uniform trend through out the week and peak flow in the evening being more than in the morning. The similarity shows that vehicular flow was the main event exhibited on the road and that the other events were negligible and most of them were road side friction factors. A representation of vehicle flow on Oginga Odinga Road link is as shown in Figure 4.



[Fig.4: Vehicle Flow on Oginga Odinga Road Link]

Sensor trigger spectrum on Oginga Odinga Road link was also examined. Triggers on both sensor A and B are as shown in Figure 5. The graph shows a slight discrepancy but the sensor balance was greater than 95% hence the trigger spectrum shows an accurate reperesentation of event flow. Event flow was taken as any event recorded by the road classifiers without exclusiely representing traffic flow. The classifiers also recorded events as a result of other features like people and animals stepping on the cables. This explained the discrepancy in trigger A and B.



[Fig.5: Trigger Spectrum on Oginga Odinga Road Link]

C. Vehicular Classification

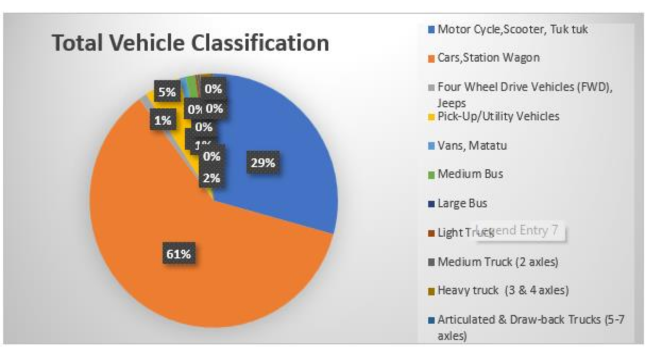
Classification of vehicles moving on urban road links was done according to the MTE user manual classification as: Motorcycle or scooter or tuktuk, car or station wagon, four-wheel drive vehicles or jeeps, pick-ups or utility vehicles, vans or matatus, medium buses, large buses, light trucks, 2 axle medium trucks, heavy trucks (3-4 axles), articulated and drawback trucks (5-7 axles), and other vehicles comprising tractors among others.

The aforementioned vehicular categories were numbered from 1 to 12 as shown in Table 4.

Table 4: Summary of Classification of Vehicles of All Classes

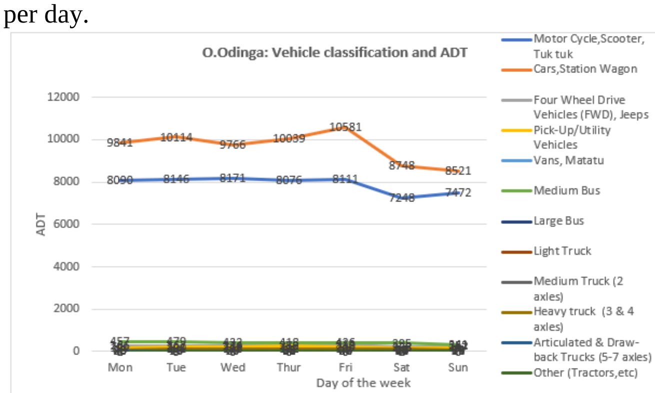
	1	2	3	4	5	6	7	8	9	10	11	12	Total
Bangladesh	3727.6	6848.6	138.8	757.6	116.6	151.4	4.4	47.2	23.4	75.2	14.6	6.4	12011.8
Elementaita	3076.6	7048.0	95.0	680.0	168.8	81.0	4.0	26.0	26.8	104.0	8.2	6.8	11325.2
Kabarak	2131.8	8636.4	101.4	538.6	78.8	51.6	2.0	24.2	5.8	27.4	3.8	3.0	11604.8
Kaptembwa	7613.4	2367.4	47.6	123.2	17.6	286.4	0.8	10.0	7.2	25.8	4.6	4.2	10508.2
Lanet-Ndundori	2799.4	8651.4	118.4	570.8	103.4	67.4	2.6	22.8	11.4	30.4	5.0	2.6	12385.6
Moi	5022.0	7241.6	186.8	172.4	53.6	274.4	2.6	15.8	13.0	46.0	8.8	6.0	13043.0
Njoro	2874.2	7241.4	76.2	608.2	67.6	61.2	3.0	23.6	12.2	37.2	4.2	4.0	11013.0
Nyahururu	4334.6	17242.6	359.6	784.8	267.8	253.8	19.0	62.6	42.2	106.8	29.0	28.4	23531.2
Oginga Odinga	8118.8	10068.2	278.6	212.4	43.6	442.4	2.0	37.4	30.6	111.2	25.4	32.8	19403.4
PGH	4767.0	9141.8	212.6	375.4	57.6	190.8	3.4	31.4	14.2	44.8	9.8	11.6	14860.4
Nakuru-Eldoret 1	3165.4	4977.4	107.2	1028.6	172.0	143.0	4.6	58.4	276.6	539.2	176.8	23.2	10601.8
Nakuru-Eldoret 2	898.4	7597.8	104.6	749.0	108.8	32.4	3.4	28.8	160.4	246.8	14.6	6.4	9951.4
Eldoret-Nakuru 1	1117.0	7037.8	64.8	1151.6	183.6	42.6	10.8	39.2	40.0	846.8	25.4	16.2	10575.8
Eldoret-Nakuru 2	2855.0	4408.4	51.0	632.6	80.6	86.8	8.2	20.8	26.4	407.4	11.8	1.6	8590.6
Week Day Average Vol	3750.0	7751.0	139.0	599.0	109.0	155.0	5.0	32.0	49.0	189.0	24.0	11.0	12815.0

Moreover, the results emanating from the observation made in all road links in Nakuru City are illustrated in Figure 6. The results indicated that cars and station wagons accounted for 61% of all the vehicles. Twenty-nine percent (29%) were motocycles, scooters, and tuktuks. These two classes accounted for the largest proportion of all vehicles which was 90% as shown in figure below. Pickup and utility vehicles accounted for 5% , The rest of he vehicles accounted for the remaining 5%.



[Fig.6: Total Vehicular Classification in Oginga Odinga Road Link]

It was revealed as shown in Figure 7 that, in Oginga Odinga Road link, cars and station wagons were the most vehicles with an ADT averaging 10,000 vehicles per day during the week and 8,500 per day over the weekends, followed by class 1 with an ADT averaging 8000 vehicles per week day and 7,000 per day over the weekends. All other vehicle classes had low ADT with medium buses accounting for an average of 400 vehicles per day.



[Fig.7: Vehicular Classification and ADT on Oginga Odinga Road Link]

D. Traffic Speed

All road links studied were within an urban area (Nakuru City) where the motorists were expected to drive at a maximum speed of 50km/hr.

According to the results shown in Figure 8, most drivers were observed to drive at speed limits of

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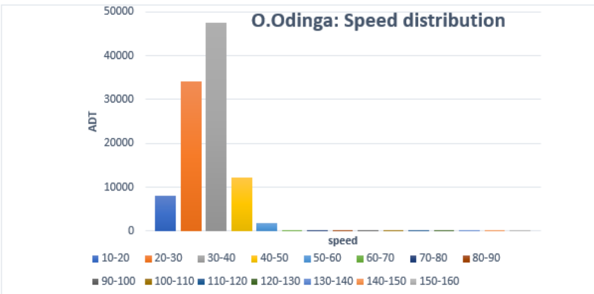
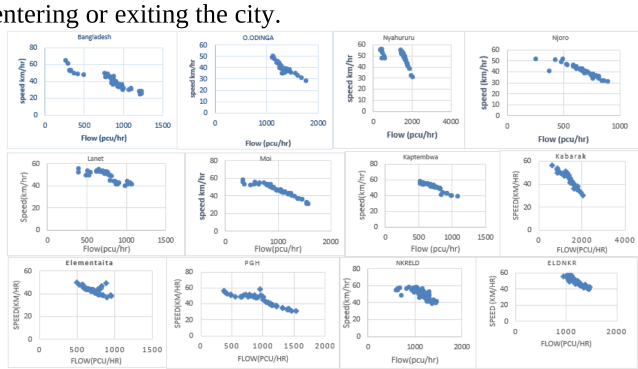
between 10 km/hr and 60km/hr. The free flow speed of these sections was determined to be 60km/hr. Ninety-eight percent (98%) of the drivers drove at speeds ranging from 10km/hr to 50km/hr while 8% drove at speeds of between 10km/hr and 20km/hr; 33% at 20km/hr to 30km/hr; 46% at 30km/hr to 40km/hr, and 11% at 40km/hr to 50km/hr. It was further established that 2% of the vehicles were moving at relatively high speed ranging from 50km/hr to 60km/hr. The vehicles that were driven at speeds greater than 60km/hr were assumed to be negligible and were consequently considered as outliers hence excluded from further analysis.



[Fig.8: Speed Distribution on Oginga Odinga Road Link]

The plotted speed flow graphs as illustrated in Figure 9 demonstrate a similar trend in all the road links in Nakuru City. There was a corresponding decrease in speed of traffic when the traffic flow increased and the relationship between the two constructs demonstrated a linear trend. According to the greenshield model the speed flow curve is supposed to be parabolic. The plots of curves for all road links in Nakuru City showed an almost linear relationship of inverse proportionality. The trends give an exposition of the road links operating at flows less than their respective capacity flows. Consequently, the parabolic curves were not witnessed in the stated sections. The studied road links had no traffic congestion and were acclaimed to exhibit high levels of service between A and C within the studied period of time. By the virtue of being a relatively young city (it was awarded the city status in 2021 (Damary, 2021)) [1], Nakuru City rarely experiences traffic congestion on its road links. The dual carriageway was identified to be the section exhibiting capacity flow, a fact that was attrubuted to intersections when entering or exiting the city.

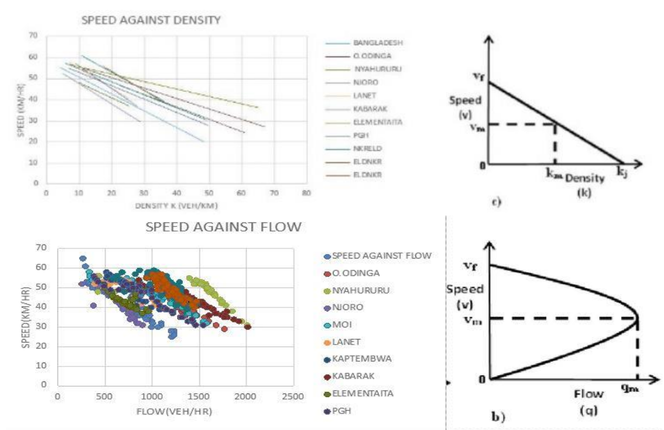


[Fig.9: Traffic Flow and Vehicle Speed on All Road Links in Nakuru City]

E. Speed Density Relationships

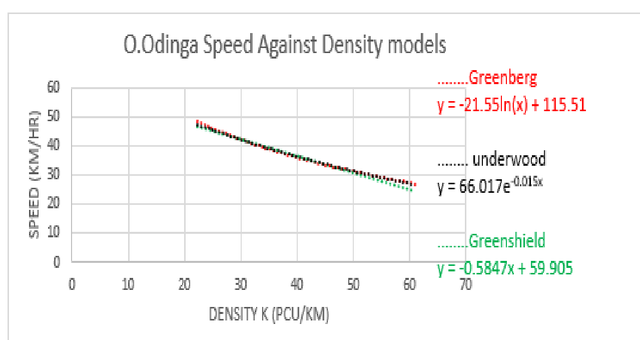
Greenshield, Greenberg and Underwood models were used to examine the traffic flow in the road links in Nakuru City.

According to the results shown in Figure 10, the stated three models illustrated a strong relationship among the variables. The R^2 value of the Greenshield model demonstrated the most significant speed-density relationship.



[Fig.10: Speed, Density and Flow Relationships on Road Links in Nakuru City]

The Greenberg, Underwood, and Greenshield models are represented by the red, black, and green curves respectively as shown in Figure 11. The data collected from the site was of speeds between 20km/hr and 50km/hr and a density ranging from 20pcu/km to 60 pcu/km. The models showed an almost similar trend as the flow values exhibited high level of service. The results shown in Figure 11 represents Oginga Odinga Road which is one of the key road links in Nakuru City. It is apparent from the pertinent results that, there existed a negative relationship between vehicular speed and and density when all the three models were employed as shown in Figure 11. The results meant that, when the density of vehicles flowing on the Oginga Odinga Road link increased, the speed of vehicles flowing on the road link reduced.



[Fig.11: Relationship between Speed and Density on Oginga Odinga Road Link]

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The results emanating from the three speed-density models (Greenshield, Greenberg, and Underwoood) for each of the surveyed 12 road links in Nakuru City are illustrated in Table 5.

Table 5: Speed-Density Models

Road Link	Greenshield		Greenberg		Underwood	
	Model	R^2	Model	R^2	Model	R^2
Njoro	y = -0.9642x + 57.203	R^2 = 0.822	y = -13.95ln(x) + 79.503	R^2 = 0.5718	$y = 60.56e^{-0.024x}$	R^2 = 0.8196
Elementaita	y = -0.7189x + 55.19	R^2 = 0.6873	y = -11.94ln(x) + 76.576	R^2 = 0.6909	$y = 57.107e^{-0.017x}$	R^2 = 0.49
Bangladesh	y = -0.7974x + 58.594	R^2 = 0.7989	y = -14.31ln(x) + 83.377	R^2 = 0.6893	$y = 62.493e^{-0.02x}$	R^2 = 0.6276
Kaptembwa	y = -1.0722x + 66.649	R^2 = 0.7599	y = -16.31ln(x) + 94.057	R^2 = 0.7263	$y = 70.219e^{-0.022x}$	R^2 = 0.4556
PGH	y = -0.6336x + 59.254	R^2 = 0.7325	y = -13.49ln(x) + 85.185	R^2 = 0.6792	$y = 62.2e^{-0.015x}$	R^2 = 0.5344
Nyahururu	y = -0.3521x + 59.107	R^2 = 0.6708	y = -6.153ln(x) + 68.642	R^2 = 0.315	$y = 61.212e^{-0.008x}$	R^2 = 0.6135
Eld-Nkr	y = -0.9162x + 71.755	R^2 = 0.731	y = -23.11ln(x) + 122.79	R^2 = 0.7486	$y = 77.907e^{-0.019x}$	R^2 = 0.6421
Nkr-Eld	y = -0.853x + 70.007	R^2 = 0.6572	y = -18.02ln(x) + 106.26	R^2 = 0.5785	$y = 74.946e^{-0.017x}$	R^2 = 0.4372
Kabarak	y = -0.495x + 60.312	R^2 = 0.7681	y = -15.53ln(x) + 97.286	R^2 = 0.6405	$y = 64.285e^{-0.012x}$	R^2 = 0.537
Oginga Odinga	y = -0.5847x + 59.905	R^2 = 0.6932	y = -21.55ln(x) + 115.51	R^2 = 0.8597	$y = 66.017e^{-0.015x}$	R^2 = 0.5365
Lanet-Ndundori	y = -0.9355x + 64.097	R^2 = 0.6361	y = -13.68ln(x) + 86.59	R^2 = 0.5444	$y = 67.024e^{-0.02x}$	R^2 = 0.7193
Moi	y = -0.62x + 60.859	R^2 = 0.8701	y = -12.59ln(x) + 84.75	R^2 = 0.6772	$y = 63.779e^{-0.014x}$	R^2 = 0.6681

Greenshield model showed the strongest relationship, and was as such, used to determine the flow parameters including free flow speed, jam density, maximum flow and headway on maximum flow in all road links in Nakuru City. The results to this effect are as shown in Table 6.

Table 6: Free Flow Speed, Jam Density, Maximum Flow, and Headway on Maximum Flow

	Free flow speed V_f, (km/hr)	**Jam density, K_j (pcu/km)**	**Speed at Max flow, Vo (km/hr)**	**Density at Max flow, Ko (pcu/km)**	**Max flow, q_{max} (pcu/hr)**	**Headway on max flow, h (sec)**
Njoro	57.203	59.327	28.6015	29.6635	848.4206	4.243178
Elementaita	55.19	76.77	27.595	38.385	1059.234	3.398682
Bangladesh	58.594	73.48	29.297	36.74	1076.372	3.344569
Kaptembwa	66.649	62.161	33.3245	31.0805	1035.742	3.475769
PGH	59.254	93.52	29.627	46.76	1385.359	2.598605
Nyahururu	59.107	167.87	29.5535	83.935	2480.573	1.451278
Eldoret-Nakuru	71.755	78.318	35.8775	39.159	1404.927	2.562411
Nakuru-Eldoret	70.007	82.072	35.0035	41.036	1436.404	2.506259
Kabarak	60.312	121.842	30.156	60.921	1837.134	1.959574
Oginga Odinga	59.905	102.454	29.9525	51.227	1534.377	2.34623
Lanet-Ndundori	64.097	68.516	32.0485	34.258	1097.918	3.278935
Moi	60.859	98.16	30.4295	49.08	1493.48	2.410478
Q= uk, h= $1/q$, $V_0 = V_f/2$, $K_0 = K_f/2$, $q_{max} = K_j \cdot V_f/4$						

The free flow speed of all the road links in Nakuru City was between 50km/hr and 80km/hr. The Eldoret- Nakuru- Nairobi dual carriage road had the highest free flow speed that ranged from 70km/hr to 80km/hr.

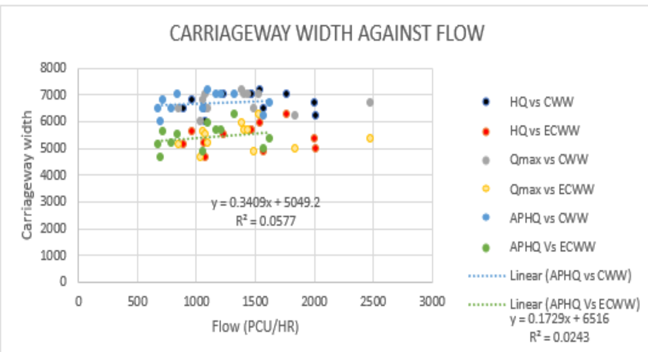
This road link had few side friction factors close to the road hence the higher free flow speeds as shown in Table 6. On the other road links, Kaptembwa, Lanet-Ndundori, Moi, and Kabarak had the highest free flow speed of between 60km/hr and 70km/hr while the other road links had a free flow speed of between 50km/hr and 60km/hr.

F. Impact of Carriageway Width Reduction on Road Capacity

Side friction on the road links in occupies part of the carriageway constricting the effective carriageway for vehicles to pass. This affects the driver's behaviour since drivers drive through these sections with a lot of caution and at reduced speeds. The results in respect of carriageway width reduction and road capacity on road links in Nakuru City are presented in Table 7 and Figure 12.

Table 7: Carriageway Width Reduction and Road Capacity

Road Link	Highest Q Recorded	Average Peak Hour Q	Qmax	Effective CWW			% Reduction
Njoro	896	674.50	848.4206	5121.475		40.5	21.21%
Elementaita	960	711.93	1059.234	5628.071		43.23214	17.23%
Bangladesh	1232	845.07	1076.372	5531.106		40.32143	20.98%
Kaptembwa	1080	698.71	1035.742	4654.448		51.82143	22.43%
PGH	1540	1103.11	1385.359	5970.681		43.08929	17.07%
Nyahururu	2008	1623.00	2480.573	5352.771		48.6	20.11%
Eldoret-Nakuru	1468	1207.50	1404.927	5663.581		48.57143	19.09%
Nakuru-Eldoret	1468	1168.00	1436.404	5663.581		49.39286	19.09%
Kabarak	2012	1570.67	1837.134	4977.274		42.32143	19.51%
Oginga Odinga	1764	1322.83	1534.377	6284.75		40.14583	19.58%
Lanet-Ndundori	1068	788.50	1097.918	5192.488		49.66071	20.12%
Moi	1576	1054.25	1493.48	4903.138		47.21429	24.57%



[Fig.12: Relationship between Carriageway Width and Traffic Flow]

According to the results shown in Figure 12, the model depicting carriageway width (CWW) against Qmax was not significant. It was also established that the trends in the two variables were not related since $R^2 < 0.5$. Interpretively, the maximum flow in the road links in Nakuru City was not affected by the existing carriageway width. Moreover, it was revealed that the relationship between ECWW and CWW against APHQ had a higher R^2 value and there. It was further observed that, there existed a weak yet significant relationship between average peak hour flow and carriageway width ($R^2<0.5$).

IV. CONCLUSION

This macroscopic traffic flow analysis of Nakuru City's road network yielded quantifiable evidence of side friction impacts on urban mobility patterns. Data collected across 11 road links revealed that pedestrian activity constitutes 62% of all recorded friction events, with vehicular composition dominated by cars/station wagons (61%) and motorcycles/tuk-tuks (29%). Through comparative analysis of traffic flow models, the Greenshield model demonstrated superior reliability with R^2 values exceeding 0.65 across measured links, while speed distributions indicated 98% of vehicles operating within 10-50 km/hr range, substantially below theoretical capacity flows.

Analysis of side friction effects produced measured carriageway width reductions of 17.07-24.57%. However, regression analysis yielded R^2 values below 0.5 for the relationship between carriageway width and maximum flow rates (Qmax), indicating limited direct correlation between width reduction and capacity impacts. The measured peak hour flows ranged from 674.5 to 1,623.0 PCU/hr across the studied links, with corresponding maximum flows (Qmax) of 848.4 to 2,480.6 PCU/hr derived from the calibrated Greenshield model parameters.

These quantified findings establish a baseline for evidence-based transportation engineering in rapidly developing urban centers. The demonstrated relationships between measurable friction factors and traffic flow characteristics provide a framework for capacity analysis and infrastructure planning. Future research opportunities include development of more sophisticated numerical models incorporating dynamic friction effects and longitudinal studies tracking flow pattern evolution as urban development progresses.

The methodologies and results presented contribute to the engineering knowledge base for sustainable transportation system design in emerging cities.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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