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Research Paper

Quantifying the impact of static and dynamic side friction on urban traffic performance in Hilla city

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ABSTRACT

This study investigates the impact of side friction (SF) on traffic movements for selected urban roads in Hilla, focusing on how static and dynamic friction elements influence traffic flow and speed. The primary SF elements observed include parked vehicles and pedestrian movements with more dynamic interactions, such as erratic road crossings. Traffic data collection was conducted on four distinct Hilla streets using elevated video cameras that recorded traffic volume, vehicle speed, and SF events. Data recording occurred on Sundays, Mondays, and Wednesdays, both in the morning and in the evening. An analysis of the recorded data revealed significant variations in traffic behavior due to SF elements. On streets with high commercial activity and educational centers, a notable reduction in average vehicle speed was found to be correlated with periods of high SF activity. During the busiest hours, the speed reduction reached 51% in comparison to periods of low SF activity. This substantial impact underscores the sensitivity of urban traffic flow to side friction factors, particularly during peak hours. Dynamic SF events, such as pedestrians crossing roads erratically, had the highest frequency during evening hours, aligning with the end of business and school activities.

1. Introduction

The degree of friction between traffic flow and activity on the side(s), and occasionally across or within the traveled road, is described by a composite variable called side friction, as defined by [1]. Various studies have been conducted on these problems, revealing that several factors contribute to the worsening of traffic conditions. There is often a great deal of activity on and alongside these roads, which affects how they operate. The forms of side friction vary and may include buses parked on the side of the road, pedestrians randomly crossing the road or walking along its side, and numerous entry and exit points for vehicles to and from the street [1]. In the study [2], a difference was found in the distribution of the number of side-friction elements through the cross-section of the road, to minimize the effects of roadside friction factors on traffic performance, the research-based information and findings from this study can be used in setting out guidelines while imposing some restrictions to eradicate an occurrence and the proliferation of roadside friction elements. The types of side friction elements varied in each research; the friction elements were limited to pedestrians who walked on the side of the road or crossed it, buses that stopped at bus stops and vehicles that stopped temporarily on the side of the road according to [3]. Traffic congestion in urban areas, especially in developing countries, presents a significant challenge for urban planners and traffic management authorities [4]. The phenomenon of side friction (SF), which encompasses a variety of activities and elements occurring near or within the roadway, is a critical factor influencing traffic flow and road capacity. These SF parameters must be carefully considered in urban traffic management and planning for their effects on traffic flow, overall safety, and road efficiency, as recommended by [5]. The current literature shows that different forms of SF, including on-street parking, pedestrian movements, and vehicle maneuvering into and out of curbside spaces, have a substantial impact on the efficiency of urban road networks. For instance, [1] identified roadside friction elements such as parked cars and pedestrian facilities as major causes of traffic disruptions in Asian cities. Similarly, [6] pointed out that SF causes a considerable decline in road capacity and is therefore a critical factor in traffic modeling and analysis. However, there is still a lack of studies that provide a holistic assessment of both static and dynamic SF factors across different urban areas. Previous research, including the work of Munawar [6] on Indonesian roads, has mainly focused on either static or dynamic factors rather than their combined effects. To this end, the present research contributes to the body of knowledge by extending the analysis to include both types of factors and examining their combined influence in the context of Hilla City, Iraq, where the mixture of commercial, educational, and residential activities creates a complex traffic environment. The novelty of this study is that it uses video recording for real-world data collection and complex analytical models in the analysis of the data. This paper presents a detailed analysis of the impacts of different types of SF on traffic flow by collecting and analyzing traffic data from different urban roads in Hilla. The streets chosen for the study were 60th Street, 40th Street, Doctors Street, and Al-Mahkamh Street, which offer a rich variety of urban settings with different levels of SF activities. In addition to presenting empirical evidence of the effects of SF, this study also suggests some practical suggestions for reducing these effects. Based on the specific characteristics of each road segment, the research provides specific recommendations for improving urban design and traffic operations, such as better pedestrian facilities, managed parking areas, and greater traffic policing. These recommendations are important in the improvement of the urban mobility and transport systems that are more efficient and sustainable.

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Nomenclature

FFS	Free flow speed (km/hr)	v/c	Volume-to-capacity ratio
$FRIC$	Friction unit	Wi	Weight coefficient of friction elements
LOS	Level of Service	x	Independent variable (side friction frequency, events/hr)
NEE	Number of entry–exit vehicle maneuvers (events/hr)	y	Dependent variable (mean vehicle stream speed, km/hr)
N_i	Number of parked or stopped vehicles (events/hr)	*Greek Symbols*	
N_P	Number of pedestrians (events/hr)	α	Regression constant/intercept
NWN	Number of wrong-way or opposite-lane vehicles (events/hr)	β	Regression coefficient (slope)
PA_i	Projected area of the parked vehicle type (m²)	μ	Mean or average value
PA_p	Projected area of a pedestrian (m²)	*Subscripts*	
PEU	Pedestrian Equivalent Unit	AM	Al-Mahkamh Street
$PSPU$	Pedestrian-stopped/parked vehicle units (events/hr)	DR	Doctors Street
R^2	Coefficient of determination	AD	Adam Street
$RSFI$	Roadside Friction Index	40	40th Street
SF	Side friction (events/hr)	max	Maximum observed value
veh/hr	Vehicles per hour	avg	Average condition

Bang [1] studied identifying roadside friction elements usually noticed along urban roads in Asian countries. These elements were parking and access to roadside premises, pedestrians, and vehicles stopping on shoulders. Bitangaza et al. [6] analyzed the effect of side friction elements on the performance of the traffic flow characteristics, particularly the road capacity and speed. The study was conducted in several urban areas; microscopic and macroscopic analysis was performed in this study, considering all the factors of side impedance.

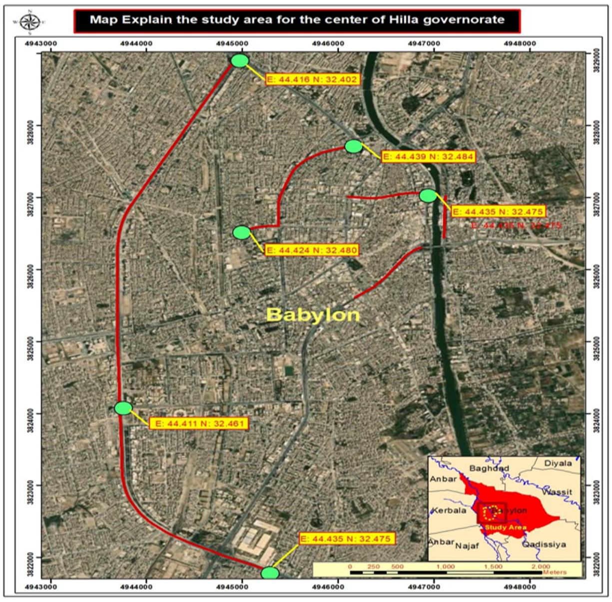

Figure 1. Hilla Governorate (Location of the selected data point).

Also, the individual effect of each impedance element on the traffic factors was studied microscopically. Munawar[7] found that side friction factors like on-street parking, U-turn vehicles, bus stopping anywhere on the roadway, and exit/entry vehicles, and considered that their influence was more than those anticipated by the IHCM. This study aims to investigate the impact of side friction in selected urban streets in Hilla. This study aims to investigate the impact of SF on traffic movements, focusing on the intricate dynamics between static and dynamic SF elements and their effects on traffic speed and behavior. Although numerous studies have explored the impact of side friction on urban traffic, most have focused either on static or dynamic elements in isolation. Furthermore, limited attention has been given to the combined effects of these elements within complex urban settings such as Hilla. There is a lack of comprehensive, real-world data-driven studies that evaluate both static and dynamic side friction components together and assess their impact on traffic flow under mixed land use and congestion conditions.

1.1 Literature review

In their study, [8] found that side friction (SF) is one of the important factors that lead to the decrease in the capacity of the road. They pointed out that SF affects undivided streets more than divided ones since the latter are usually characterized by more controlled traffic motions. This notion was also supported by [4], who pointed out that SF characteristics have not been incorporated into the Highway Capacity Manual HCM (2016), which provides very specific rules for capacity calculations and Level of Service (LOS) based on speed and other parameters. Nevertheless, the HCM corrections for determining the capacity and LOS are not based on SF components. Gulivindala et al.[9] assessed the impact of SF factors on traffic performance, such as speed and capacity and for the first time proposed a new parameter called Friction Index (FRIC) to incorporate the total influence of all SF variables.[4] investigated the effects of side friction on the capacity of undivided streets in metropolitan areas and estimated that the capacity was decreased by about 60.73% due to friction, which included on-street parking, pedestrian activities, and non-motorized vehicles (NMVs). A comparison of the IHCM (2023) values with field observations in Indonesia was done by Munawar[7], and it was observed that there was a change of trend in capacity at high levels of friction. Some studies [10, 11] have investigated the effects of pedestrian crossing flow rates on urban road capacity. Kadali et al.[10] reported that there was a decline in capacity by 30% – 37% due to high pedestrian crossings. Golakiya et al. [11] also revealed that there was a reduction of about 32%. This effect, according to papers [12, 13], is completely different in each country because of the driving culture and the consciousness of drivers to pedestrians. Pu et al. [13] proposed a delay model, which showed that delay increases by 33 seconds per kilometer with approximately 1000 bicycles mixed in traffic. It is important to note that SF parameters are often present in combinations on urban streets, which leads to a cumulative impact on traffic flow rather than individual effects. Although many studies have used multiple SF factors in the development of speed models, none of the studies have looked at the combined effect of all these on the capacity of urban streets, both divided and undivided. This research [14] revealed that the existence of motorcycles does influence the peak flow rates at signalized intersections in Malaysia. The research also established that motorcyclists have distinct traveling patterns, which include changing lanes and forming a platoon at the stop lines, which otherwise alter the traffic flow. In a case study carried out in India, researchers [15, 16] applied the VISSIM simulation model to analyze the effects of side friction on traffic movements and concluded that side friction led to delays on the road segments. The effect of side friction on street capacity was investigated by several works [17–20] in India. Their results showed that speeds were reduced by 49-57% for segments with bus stops and 45-67% for segments with on-street parking. A few papers [21–23] analyzed the effects of roadside friction elements—on-street parking, pedestrian crossings, and non-motorized vehicles—on traffic flow, speed, capacity, and LOS on Varanasi's urban arterials. Using nine hours of video data and Greenshield's speed–density model, they compared a low-friction base section with a high-friction section. They found up to 40% capacity loss and deterioration to LOS E, emphasizing the importance of controlling side friction in congested corridors. Researchers [24, 25] conducted an in-depth investigation on the impacts of side friction elements, including pedestrian activity, on-street parking, temporary stopping, and entry-exit maneuvers, on the performance of both divided and undivided urban streets in Al-Najaf City, Iraq. Their results indicated that under very high side friction conditions, traffic speed reduced by up to 47% and road capacity decreased by 49%. The study also introduced a speed prediction model incorporating side friction intensity, traffic flow, and street width. Notably, their findings confirm that undivided streets are more significantly affected by side friction compared to divided ones, due to less controlled access and greater interaction with roadside activities. Side friction levels have been classified since 1993 in the Indonesian Highway Capacity Manual into High and Low Levels. Based on the variation in the speed data in the Indonesian Highway Capacity Manual, the side friction was classified at four levels. Side friction has no noticeable impact on the vehicles' average speed at very low levels. There is a significant decrease in the average between 500 and 1000 incidents per hour. When 1000 incidents per hour are detected, a significant percentage of the average speed is reduced. Table 1 indicates a classification of side friction level and the percentage of average speed reduction for combined data. At a greater amount of side friction, roughly 51% of the speed reduction has been noticed.

Table 1. Levels of side friction at different speeds [9],

SF (Events/hr)	**Level of side friction**	**Average stream speed** (km /h)	**Percentage reduction in average speed**
00 – 500	Low	34	-
500 – 1000	Medium	31	20
1000 – 2000	High	24	38
> 2000	Very high	19	51

2. Methodology

The research design for this study was very precise to examine the effects of side friction (SF) on traffic dynamics in some urban streets of Hilla. This involved both primary data collection and advanced statistical analysis, both qualitative and quantitative. The choice of the samples was made on four major urban roads in Hilla, namely, 60th Street, 40th Street, Doctors Street, and Al-Mahkamh Street. These roads were chosen for the study because they had different levels of SF and different traffic patterns. Video cameras were used to collect data from elevated positions at certain intervals along the roads. The cameras captured data on traffic flow rates, vehicle speeds, and the frequencies of SF events. The data was collected at specific times, including on Sundays, Mondays, and Wednesdays, and during the morning and evening peak hours. This timetable provided a full coverage of the traffic patterns during peak and off-peak times. The study defined and distinguished SF factors into two groups: static and dynamic. Static SF was defined as objects such as vehicles parked along the sides of the road, while dynamic SF included events such as people walking across the road and vehicles joining or leaving the traffic stream. The frequency and type of these SF events were then classified to determine their effects on traffic flow. An analytical framework was also developed to measure the effects of SF on traffic flow. This involved the computation of the Roadside Friction Index (RSFI) and the Friction (FRIC) unit. The RSFI was computed based on the frequency of SF elements and their weights, which describe the level of impact on traffic flow. Likewise, the FRIC unit was based on several independent variables that included pedestrians, parked vehicles, and other non-motorized objects. In order to establish the relationship between SF and traffic flow, regression models were developed. These models were based on a large dataset, which included predictors such as flow, speed, and the frequency of SF events. The regression analysis was conducted to forecast the effects of SF elements on traffic dynamics. The accuracy and reliability of the developed models were validated against a subset of the collected data. A sensitivity analysis was also performed to check the robustness of the models with respect to different conditions and to find out the important factors that can affect traffic flow due to SF most. This methodological approach enabled a better understanding of the interactions between SF and traffic dynamics, which can offer practical insights to urban planners and traffic management authorities.

2.1 Static Side Friction

To arrive at the total static side friction, the frictional forces due to the static side friction activities, such as the presence of pedestrians and parked vehicles, are combined. Following a procedure proposed by Pal et al. [2] for estimating total static side friction, equivalent pedestrian units (PEU) are calculated for each parked vehicle type within the influencing area. The expression for converting parked vehicle types into an equivalent number of pedestrian units is given in Eq. 1.

$$PEU = \frac{PA_i}{PA_p} \tag{1}$$

Where,
PEU= Equivalent pedestrian unit of the parked vehicle type.
PA_i=Projected area of the parked vehicle type.
PA_p= Projected area of the pedestrian.

Further, PEU of vehicle type is multiplied by the frequency of parked/stopped vehicle types to achieve uniformity in the measurement of static side friction. The PEU values estimate the frequency of static side friction by combining pedestrian and parked vehicles. The expression for finding the static side friction is given in Eq. 2 in terms of $PSPU$ $(events/hr)$ i.e. pedestrians and (stopped/parked) vehicles in terms of pedestrian units.

$$NPSPU = NP + \sum_i PEU_i \times N_i \tag{2}$$

Where,
$NPSPU$= Frequency of pedestrians and stopped/parked vehicles in pedestrian units.
NP = Frequency of pedestrians.
PEU_i = Equivalent pedestrian unit of the parked/stopped vehicle.
N_i = frequency of the parked/stopped vehicle.

2.2 Roadside friction index (RSFI)

Pal et al.[2] proposed the side road friction in this index. Several roadside friction elements were considered in the calculations of RSFI. Among the aspects that were taken into consideration were pedestrian crossing, Bicycles, and non-motorized vehicles, whether permanently or temporarily parked on the side of the road. All of these elements were multiplied by a different weight factor assigned to each element according to the severity of its effect on the traffic characteristics. The weight of each element was also based on the element's location on the side of the road and its distance. The side friction index can be defined as the product of multiplying the number of each side friction element by its weight over 100 meters in length. The Eq. 3 illustrates the relationship between the weight factor.

$$RSFI = \sum_{i=1}^{n} W_i \times N_i \tag{3}$$

Where:
$RSFI$ = Road Side Friction Index.
N_i = Number of (i) type friction elements in 100m road stretch.
W_i = Weight factor for (i) type roadside friction parameter.

Various friction elements impact travel speed differently based on their static and dynamic characteristics and position on the carriageway. The number of friction elements in the form of pedestrians and parked vehicles standing or crossing the carriageway within 35 meter stretch has been multiplied by a weight factor to estimate the RSFI value. Bitangaza et al. [6] developed a statistical model for variable speed based on the side friction elements as independent variables and other parameters. The friction (FRIC) unit was also designed based on four independent parameters only, namely: the bicycle element, the non-motor vehicle element, the temporarily stopped vehicle element, as well as the pedestrian flow element, as shown by Eq. 4.

$$FRIC = PED + 0.45 \times BIC + 0.08 \times NMV + 0.37 \times PSV \tag{4}$$

Where:
$FRIC$ = FRICTION
PED = Pedestrians $(No/200m/hr)$.
BIC = Bicycles $(No/200m/hr)$.
PSV = The Parking and Stopping Vehicles $(No/200m/hr)$.
NMV = Non-Motorized Vehicles $(No./200m/hr)$.

To determine the unit $(FRIC)$, weighted standard coefficients were added to the independent individual variables that have a negative relationship with the standard variable (dependent variable). Regression analysis was performed for these individual coefficients, as this analysis included the flow parameter and the elements of side friction and made them independent variables in the equation. The speed parameter was taken as a response variable.

3. Study area and data collection

The study was conducted in Hilla City, the capital of Babil Governorate in central Iraq. Hilla represents one of Iraq's rapidly urbanizing cities, where mixed land-use patterns and uncontrolled roadside activities exert significant influence on traffic flow and operational performance. The selected corridors constitute major components of the city's transportation network, linking commercial, institutional, residential, and healthcare zones that collectively define Hilla's urban mobility system. Initially, six major urban streets were identified for preliminary evaluation based on their importance within the city's mobility framework, as well as the diversity of their geometric design, traffic volume, pedestrian activity, and presence of roadside friction elements, following the recommendations of the Highway Capacity Manual (HCM, 2000; 2010).

From this set, four representative corridors were purposively selected for detailed investigation—60th Street, 40th Street, Doctors Street, and Al-Mahkamh Street—to ensure that the dataset captured the full range of side-friction intensities and traffic environments in Hilla's urban context. Figure 1 indicates the location of study area which lies in Babil Governorate. Several sites have been chosen through the city. Each of these corridors represents a distinct functional category within the city's road hierarchy:

- **60th Street:** A divided arterial within the central business district, characterized by continuous two-way flow and high commercial activity.
- **40th Street:** A corridor serving both educational and commercial land uses, with heavy pedestrian movement during school and market hours.
- **Doctors Street:** A healthcare-oriented corridor with numerous clinics and pharmacies, typically experiencing high evening congestion and frequent short-term parking.
- **Al-Mahkamh Street:** A mixed administrative and commercial route within the city center, exhibiting intense pedestrian–vehicle interaction and high side-friction activity.

Although the analysis focused on these four corridors, each was divided into several observation segments (approximately 200 meters each) and monitored under different temporal conditions. This approach produced a statistically robust and spatially representative dataset that reflects variations in geometric features, traffic demand, and adjacent land use across the city. Accordingly, the selected corridors provide a realistic cross-section of Hilla's operational traffic and side-friction characteristics, ensuring that the findings are representative of the city's broader road network. All field surveys were conducted under dry, clear weather conditions and good daylight visibility to ensure consistency and reliability of the collected data. The absence of rainfall, fog, or extreme heat minimized external variations in driver and pedestrian behavior. Therefore, any differences observed in vehicle speed or traffic flow were attributed directly to side-friction activities rather than environmental influences. Traffic surveys were performed on Sundays, Mondays, and Wednesdays, covering both morning (08:00–10:00 AM) and evening (06:00–09:00 PM) periods to encompass typical weekday conditions. The determination of peak and off-peak periods was based on the observed hourly traffic flow obtained from preliminary counts. Peak hours were defined as those in which traffic volume exceeded 80% of the daily maximum hourly flow, corresponding to 08:00–09:00 AM and 07:00–09:00 PM. Conversely, off-peak conditions were analyzed using mid-day periods such as 02:00–03:00 PM, when traffic flow was substantially lower. This classification enabled a consistent comparison of speed, flow, and side-friction effects under both congested and free-flowing traffic conditions. Traffic data were obtained using elevated video cameras strategically positioned along each corridor to continuously record vehicular movements, pedestrian crossings, and other roadside activities. The recorded footage was processed to extract classified traffic volumes, flow rates (veh/hr), and frequencies of side-friction (SF) events. These SF elements were categorized into two main types:

- **Static friction:** Activities that remain stationary or semi-stationary, such as parked vehicles, on-street vendors, or curbside obstructions.
- **Dynamic friction:** Short-term or moving interactions, including pedestrian crossings, wrong-way maneuvers, and vehicle entry–exit movements from roadside facilities.

As an illustration, Table 2 presents the classified traffic composition on 60th Street between 08:00 and 09:00 AM, showing vehicle counts at 5-minute intervals and their corresponding flow rates. Passenger cars were the dominant vehicle category, with the highest flow recorded between 08:55 and 09:00 AM (3,876 veh/hr). These observations formed the basis for evaluating congestion levels, travel speeds, and the magnitude of side-friction effects during different operating conditions. It is important to note that all data were collected within a short-term period during the spring season (March–April) under stable weather conditions.
Consequently, seasonal variations in traffic flow and roadside activity patterns were not explicitly analyzed in this study. However, this temporal consistency ensures that the results are not biased by external fluctuations in climate or daylight conditions. Future research should extend the observation period to include multiple seasons, enabling a more comprehensive understanding of how climatic and temporal factors influence side friction intensity and driver behavior.

Table 2. Hourly traffic composition and flow rate on 60th street from the College of Art Education main gate to the Al-Tamhasiyah bridge (08:00–09:00 AM).

Time	Pc	Mini_Bus	Bus	Truck	Motor	Bicycle	Three-wheel vehicle	Flow rate (veh/hr)
08:00 - 08:05	169	54	2	8	5	0	1	2868
08:05 - 08:10	154	63	2	25	14	0	4	3144
08:10 - 08:15	159	65	3	27	9	0	1	3168
08:15 - 08:20	165	58	2	24	11	0	2	3144
08:20 - 08:25	170	59	4	20	5	0	2	3120
08:25 - 08:30	173	59	2	22	5	1	3	3180
08:30 - 08:35	169	67	3	19	6	0	1	3180
08:35 - 08:40	184	71	4	24	8	0	1	3504
08:40 - 08:45	177	66	2	19	7	0	3	3288
08:45 - 08:50	197	72	3	20	5	0	2	3588
08:50 - 08:55	208	65	3	25	6	0	2	3708
08:55 - 09:00	227	69	27	19	5	0	1	3876

3.1 Analyses of urban street SF

Side friction (SF) activities were identified from video footage recorded at multiple points along a 200-meter designated observation segment. During the observation period, the frequency of pedestrian movements and on-street parking events was used to quantify the intensity of side friction in the field. Traffic flow is notably affected when vehicles are parked outside designated parking zones, and such interactions are analyzed separately due to their disruptive nature. The interaction between moving vehicles and improperly parked cars significantly contributes to lateral friction. Tables 3 and Table 4 present the maximum recorded side friction values for each section during the morning and evening periods, respectively. The overall level of friction is assessed based on the classifications provided Figures 2 and 3 illustrate the variation in side friction during the morning and afternoon periods, respectively. In the morning period Fig. 2, parking vehicles represent the dominant side-friction element throughout most of the observation window, while pedestrian activity reaches its peak around 9:00 AM before gradually declining. In the afternoon period, Fig. 3, pedestrian activity exhibits a noticeable upward trend toward the end of the observation window, whereas parking-related friction remains consistently high across the entire period. These patterns highlight the temporal variability of side-friction elements and their influence on urban traffic operations along 40 Street. During the afternoon period, the consistent demand for parking suggests increased activity likely associated with business operations and the onset of evening rush hour traffic. In contrast to the morning pattern, pedestrian activity shows a noticeable upward trend throughout the afternoon, reaching its peak toward the end of the observation window. This increase may correspond to after-work engagements, such as individuals finishing their jobs or visiting commercial areas in the afternoon. Figures 4 and 5 demonstrate the variation of the SF for both parked and pedestrian traffic for morning and afternoon periods in the Bab Al-Hussein Bridge area. Figure 6 and 7 showed that the side friction incidents are distributed along on 60 Street from AL-Thawruh Bridge to Nadir Bridge during the morning and afternoon time frames. During the morning, there are several parking-related incidents (350-450 events/hr), indicating a steady demand for parking due to work-related activities. On the other hand, pedestrian incidents are lower, fluctuating between 50 to 150 events/hr. In the afternoon, parking incidents decreased following the end of work hours, suggesting a large vehicle outflow, while pedestrian activity also declined. Figures 9 and 9 show how side friction events vary throughout the day, along Al Mahkamh Street from Bab Al Hussein Bridge to Al Hunud Bridge, reflecting the dynamics during morning and afternoon hours.

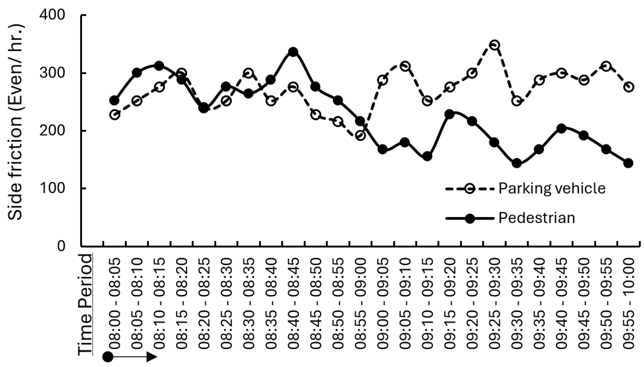

Figure 2. Side friction events over time on 40 Street (Morning Period).

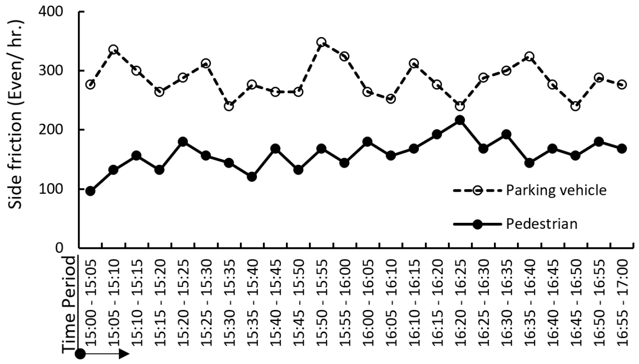

Figure 3. Side friction events over time on 40 Street (Morning Period).

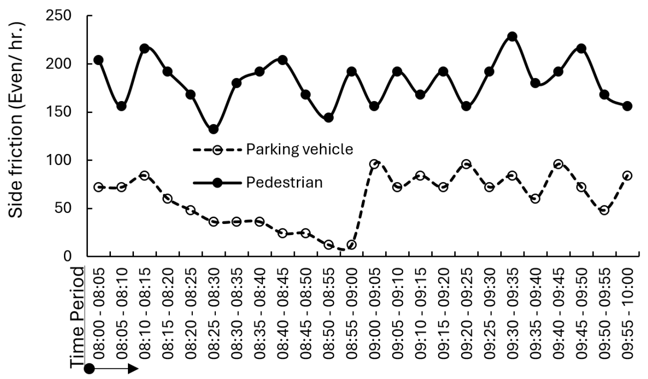

Figure 4. SF events over time on Docter Street from Bab Al-Hussein Bridge to Al-Ray Street.

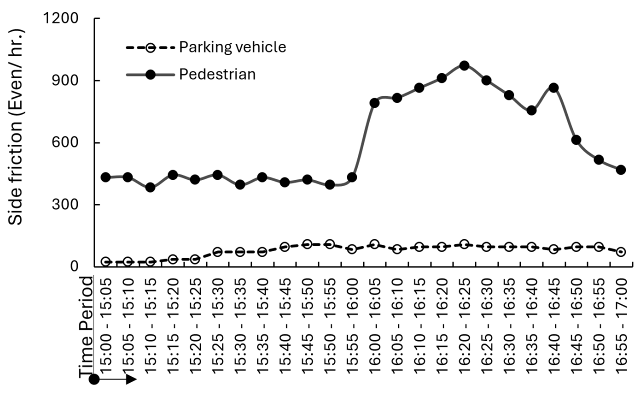

Figure 5. SF events over time on Docter Street from Bab Al-Hussein Bridge to Al-Ray Street.

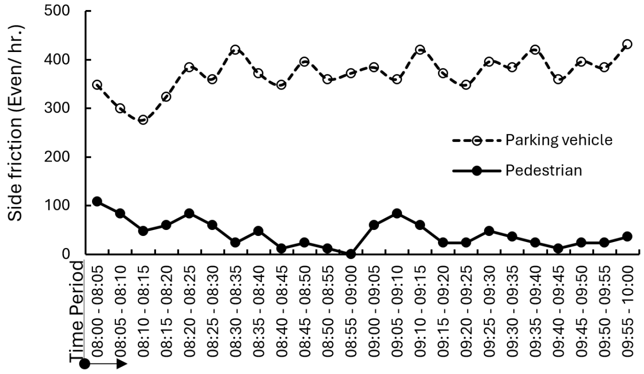

Figure 6. SF events over time on 60 Street Adam from AL-Thawruh Bridge to Nadir Bridge.

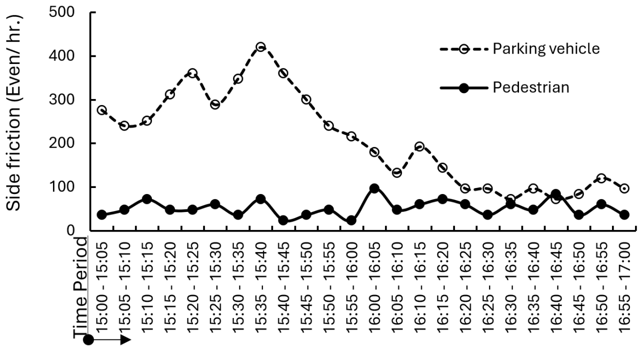

Figure 7. SF events over time on 60 Street Adam from AL-Thawruh Bridge to Nadir Bridge.

Figure 8 covering the time span from 8:00 AM to 10:00 AM, we notice an increase in pedestrian side friction events peaking at around 9:55 AM with 700 events per hour. This rise could be linked to the pedestrian traffic during morning rush hours. On the other hand, side friction caused by parked vehicles remains relatively stable with an uptick towards the end of this period, suggesting a steady buildup of parked cars as the morning unfolds.

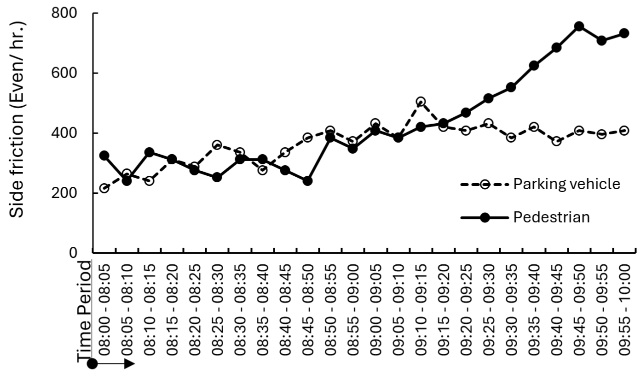

Figure 8. SF events over time on Al-Mahkamh Street from Bab Al-Hussein Bridge to Al-Hunud Bridge.

Figure 9 demonstrates the timeframe from 3:00 PM to 5:00 PM. Pedestrian events exhibited a surge starting around 3:40 PM and reaching peak levels near 900 events per hour. This reason may be attributed to the workday, which leads to increased pedestrian movement. The results from regression analysis for three chosen urban streets Doctors Street, Al-Mahkamh Street, and Adam Street, are presented in Table 5 to assess the effect of side friction elements on vehicle speed. The table shows regression coefficients, t-values, p-values, and relative weights for each variable in the models. The side friction equations derived from the data analysis show the effect of different side friction elements on speed:

Table 3. Data of side friction elements during the morning period (08:00 to 10:00 AM) for 40 Street – from Abu Khamra Intersection to Bab Al-Hussein Intersection.

Time	On-street parking	Parking vehicle (Ni) (Event/hr)	Pedestrian	Pedestrian (NP) (Event/hr)	NPSPU (Event/hr)
08:00 - 08:05	15	180	24	288	2903
08:05 - 08:10	12	144	20	240	2332
08:10 - 08:15	20	240	18	216	3703
08:15 - 08:20	13	156	23	276	2542
08:20 - 08:25	17	204	20	240	3204
08:25 - 08:30	21	252	18	216	3877
08:30 - 08:35	24	264	23	276	4111
08:35 - 08:40	21	276	29	348	4358
08:40 - 08:45	23	276	26	312	4322
08:45 - 08:50	25	300	33	396	4755
08:50 - 08:55	27	324	31	372	5079
08:55 - 09:00	21	252	35	420	4081
09:00 - 09:05	29	348	13	156	5212
09:05 - 09:10	21	252	16	192	3853
09:10 - 09:15	23	276	14	168	4178
09:15 - 09:20	32	384	16	192	5771
09:20 - 09:25	28	336	13	156	5038
09:25 - 09:30	34	408	16	192	6120
09:30 - 09:35	28	336	19	228	5110
09:35 - 09:40	24	288	15	180	4364
09:40 - 09:45	25	300	16	192	4551
09:45 - 09:50	24	288	18	216	4400
09:50 - 09:55	26	312	14	168	4701
09:55 - 10:00	23	276	13	156	4166

Table 4. Data of side friction elements during the (15:00 to 17:00) for 40 Street – from Abu Khamra Intersection to Bab Al-Hussein Intersection.

Time	On-street parking	Parking vehicle (Ni) (Event/hr)	Pedestrian	Pedestrian (NP) (Event/hr)	NPSPU (Event/hr)
15:00 - 15:05	32	384	16	192	5771
15:05 - 15:10	31	372	15	180	5585
15:10 - 15:15	35	420	15	180	6282
15:15 - 15:20	32	384	17	204	5783
15:20 - 15:25	26	312	25	300	4833
15:25 - 15:30	29	348	22	264	5320
15:30 - 15:35	27	324	21	252	4959
15:35 - 15:40	23	276	15	180	4190
15:40 - 15:45	28	336	14	168	5050
15:45 - 15:50	25	300	13	156	4515
15:50 - 15:55	22	264	17	204	4039
15:55 - 16:00	24	288	13	156	4340
16:00 - 16:05	29	348	09	108	5164
16:05 - 16:10	35	420	11	132	6234
16:10 - 16:15	30	360	10	120	5350
16:15 - 16:20	25	300	13	156	4515
16:20 - 16:25	23	276	14	168	4178
16:25 - 16:30	20	240	12	144	3631
16:30 - 16:35	21	252	10	120	3781
16:35 - 16:40	26	312	15	180	4713
16:40 - 16:45	30	360	13	156	5386
16:45 - 16:50	24	288	12	144	4328
16:50 - 16:55	27	324	10	120	4827
16:55 - 17:00	26	312	11	132	4665

Table 5. Regression Analysis and Derived Equations Demonstrating the Influence of Side Friction Elements on Vehicle Speed Across Selected Urban Streets.

Street		**Regression Coefficients**	**t-value**	**p-value**	**Relative Weights Coefficient**	**Side Friction Equation**.
Doctors	Constant	74.008	77.112	< 00.001	——-	
	PSPU	-.901	-40.332	< 00.001	1	$SF = (1 \times NPSPU) + (0.02 \times NWN)$
	Opposite NWN	00.03	00.673	00.361	00.02	
Almahkamh	(Constant)	58.331	52.770	< 00.001		
	PSPU	-00.601	-07.361	< 00.001	1	$SF = (1 \times NPSPU) + (0.402 \times NEE)$
	Entry_Exit NEE	-00.141	-03.011	00.004	00.402	
Adam	(Constant)	94.683	12.711	< 00.001		
	PSPU	-00.583	-04.71	< 00.001	1	$SF = (1 \times NPSPU) + (0.461 \times NEE)$
	Entry_Exit NEE	-00.374	-03.041	00.041	00.461	

- Doctors Street: The model reveals that Pedestrian and Stopped/ Parked Vehicle Units (PSPU) have a strong negative relationship with vehicle speed (coefficient = -0.901, $p < .001$), implying that higher PSPU values lead to lower speeds. The Number of Vehicles in the Opposite Lane (NWN) has a very small and statistically insignificant effect (p = 0.361).
- Al-Mahkamh Street: PSPU is also found to have a significant negative effect on speed (coefficient = -0.601, $p < 0.001$). Furthermore, NEE also has a negative effect (coefficient = -0.141, p = 0.004), which means that more entries and exits also decrease the speed of travel. The relative weight of NEE (0.402) shows that NEE is a significant contributor to side friction on this street.
- Adam Street: The regression model shows that PSPU and NEE are the factors that influence the speed of vehicles. PSPU has a coefficient of -0.583 ($p < 0.001$), while NEE has a relatively high coefficient of -0.374 ($p = 0.041$) and a relative weight of 0.461. The results show that PSPU is the most critical side friction factor in all the streets, while entry/exit activities (NEE) are also very important, especially on Al-Mahkamh and Adam Streets.

The derived equations assist in quantifying the total effect of side friction elements on traffic flow which is crucial for effective urban traffic management and planning. The five-minute observations in Table 6 show a clear inverse association between roadside side-friction intensity (events/h) and the stream speed (km/h) along the Al-Mahkamh Street segment (Bab Al-Hussein Bridge → Al-Hunud Bridge, 08:00–09:00). Intervals characterized by higher friction—driven by frequent pedestrian crossings, on-street parking maneuvers, and access-point ingress/egress—correspond to the lowest space-mean speeds (mid-30s km/h), whereas lower-friction windows (1,000–1,300 events/h) are associated with speeds around 40–45 km/h.

Table 6. Five-Minute Side-Friction (events/hr) and Speed (km/hr), Al-Mahkamh Street from (Bab Al-Hussein Bridge to Al-Hunud Bridge), 08:00–09:00 AM.

Time	**Side Friction** (events/hr)	**Speed** (km/hr)
08:00 - 08:05	1294.00	40
08:05 - 08:10	1178.96	45
08:10 - 08:15	1251.16	41
08:15 - 08:20	1981.28	34
08:20 - 08:25	1301.95	39
08:25 - 08:30	1796.52	35
08:30 - 08:35	1711.72	36
08:35 - 08:40	1674.08	37
08:40 - 08:45	1662.80	37
08:45 - 08:50	1826.04	36
08:50 - 08:55	2244.48	35
08:55 - 09:00	1814.00	36

Table 7. Hourly Observations of side friction components on Doctors street (08:00–10:00 AM and 2:00–3:00 PM).

Time	Pedestrain, (N_p)	Parking vehicle, (N_i)	$PSPU = PEU_i \times N_i + Passenger$	Wrong movement vehicles	SF
08:05 - 08:10	156	72	1202.16	0	1202.16
08:10 - 08:15	216	84	1436.52	0	1436.52
08:15 - 08:20	192	60	1063.8	0	1063.8
08:20 - 08:25	168	48	865.44	0	865.44
08:25 - 08:30	132	36	655.08	0	655.08
08:30 - 08:35	180	36	703.08	12	703.284
08:35 - 08:40	192	36	715.08	0	715.08
08:40 - 08:45	204	24	552.72	0	552.72
08:45 - 08:50	168	24	516.72	0	516.72
08:50 - 08:55	144	12	318.36	0	318.36
08:55 - 09:00	192	12	366.36	0	366.36
09:00 - 09:05	156	96	1550.88	0	1550.88
09:05 - 09:10	192	72	1238.16	0	1238.16
09:10 - 09:15	168	84	1388.52	0	1388.52
09:15 - 09:20	192	72	1238.16	0	1238.16
09:20 - 09:25	156	96	1550.88	0	1550.88
09:25 - 09:30	192	72	1238.16	0	1238.16
09:30 - 09:35	228	84	1448.52	0	1448.52
09:35 - 09:40	180	60	1051.8	0	1051.8
09:40 - 09:45	192	127	2586.88	0	2586.88
09:45 - 09:50	216	72	1262.16	0	1262.16
09:50 - 09:55	168	48	865.44	0	865.44
09:55 - 10:00	156	84	1376.52	0	1376.52
14:00 - 14:05	192	72	1238.16	0	1238.16
14:05 - 14:10	240	72	1286.16	0	1286.16
14:10 - 14:15	288	84	1508.52	0	1508.52
14:15 - 14:20	264	60	1135.8	12	1147.8
14:20 - 14:25	336	48	1033.44	0	1033.44
14:25 - 14:30	288	36	811.08	0	811.08
14:30 - 14:35	372	36	895.08	0	895.08
14:35 - 14:40	420	36	943.08	0	943.08
14:40 - 14:45	468	24	816.72	0	816.72
14:45 - 14:50	528	24	876.72	0	876.72
14:50 - 14:55	480	12	654.36	0	654.36
14:55 - 15:00	456	12	630.36	0	630.36

Figure 10 presents the scatter plot illustrating the relationship between side friction (events/hr) and vehicle speed (km/hr), revealing a strong inverse linear association. The fitted regression line $y = -0.0274x + 57.436$ indicates that an increase of 100 side-friction events per hour is associated with an approximate reduction of 2.74 km/hr in mean stream speed. The coefficient of determination ($R^2 = 0.83$) shows that about 83% of the variability in vehicle speed is explained by changes in side friction, underscoring its substantial influence on traffic performance along this section. The variable x represents the total number of side friction events per hour ($events/hr$), while y denotes the average vehicle stream speed (km/hr). The slope value of -0.0274 implies that for every single increase in side friction event per hour, the mean stream speed decreases by 0.0274 km/hr. Practically, this means that an additional 100 side friction events per hour would reduce the average speed by approximately 2.74 km/hr. Such a rate of decline is substantial in urban conditions, where even minor speed reductions can lead to noticeable congestion, increased travel time, and higher delay costs. The intercept value (57.436 km/hr) represents the expected free-flow speed under friction-free conditions on the studied segment, which aligns well with observed speeds for arterial streets in medium-sized Iraqi cities. Table 7 presents the observed side friction elements on Doctors Street during two peak periods: morning (08:00–10:00 AM) and afternoon (2:00–3:00 PM). The Table 7 includes pedestrian volumes (Np), parked vehicles (Ni), calculated pedestrian-stopped vehicle units (PSPU), and the number of wrong-movement vehicles. The total side friction (SF) is derived by combining PSPU and any additional disruption from illegal vehicle movements. The data show that side friction peaks occurred during times of high pedestrian activity and vehicle parking, significantly affecting traffic flow conditions on the street. Tables 8 and 9 show the impact of SF factors such as parked vehicles and pedestrian activities on city traffic flow, using video cameras to collect data on traffic volume, vehicle speed, and SF events across various streets. The results indicated a significant reduction in vehicle speeds during peak SF occurrences, particularly in areas with heavy commercial and educational activities, with speed reductions reaching up to 51% compared to periods of low SF.

Table 8. Level of SF in the morning period.

Road No.	Street name	Segment No.	Length(m)	Length(m)	Level of SF	Percentage reduction in average speed
1	40 Street	1 2	523 520	6120 5236	Very high	51
2	Doctors Street	1	768	1586	Very high	51
3	60 Street Adam	1 2	1284 1282	6321 5615	Very high	51
4	Al-Mahkamh Street	1 2	1512 1510	7743 7604	Very high	51

Table 9. Level of SF in the evening period.

Road No.	Street name	Segment No.	Length(m)	Length(m)	Level of SF	Percentage reduction in average speed
1	40 Street	1 2	523 520	6354 5735	Very high	51
2	Doctors Street	1	768	2541	Very high	51
3	60 Street Adam	1 2	1284 1282	6523 5266	Very high	51
4	Al-Mahkamh Street	1 2	1512 1510	7509 7484	Very high	51

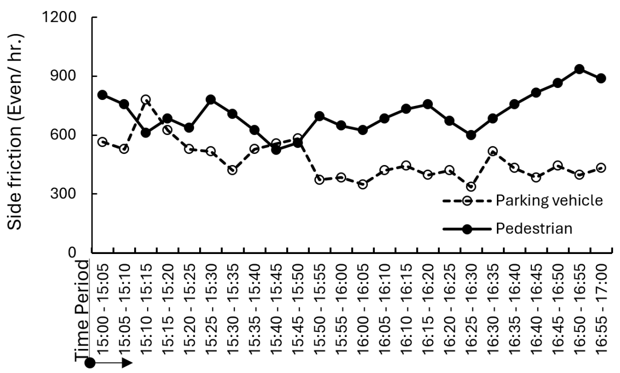

Figure 9. SF events over time on Al-Mahkamh Street from Bab Al-Hussein Bridge to Al-Hunud Bridge.

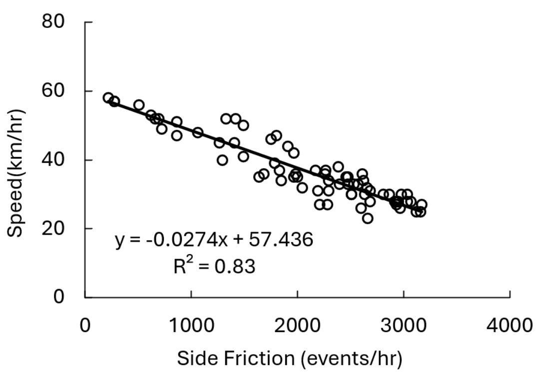

Figure 10. Side Friction vs. Vehicle Speed on Al-Mahkamh Street.

4. Conclusion

This study conducted a comprehensive evaluation of the impact of roadside friction (SF) elements on traffic flow performance within selected urban corridors in Hilla City. The results demonstrated that both static and dynamic friction activities—such as pedestrian crossings, on-street parking, vehicle entry and exit movements, and wrong-way maneuvers—have a significant and measurable effect on vehicle speed and overall traffic efficiency. The regression analysis revealed that pedestrian units and parked/stopped vehicle units (PSPU) exerted the strongest influence on speed reduction across all surveyed streets, with regression coefficients ranging between –0.58 and –0.90 and R^2 values exceeding 0.80. This indicates that side friction pertains to more than 80% of the variation in vehicle speed, highlighting its dominant role in urban traffic performance. Among all corridors, Al-Mahkamh street exhibited the highest friction intensity (over 7,700 events/hr), resulting in a 51% reduction in average speed, particularly during peak hours. From a scientific standpoint, the developed regression framework not only enhances the accuracy of traffic flow prediction under varying friction levels but also establishes a foundation that can be integrated with microscopic simulation platforms, such as PTV VISSIM, for advanced scenario testing. Practically, the results underscore an urgent need to implement traffic management strategies for reducing roadside disturbances—such as enforcing parking regulations, relocating informal commercial activities, and improving pedestrian crossings—to optimize travel speed and increase roadway capacity. In summary, this research enriches the understanding of how side friction deteriorates traffic performance in mixed-use urban environments. The adopted methodology and findings may serve as a decision-support tool for urban planners and transportation authorities to develop sustainable and efficient mobility solutions in rapidly growing cities like Hilla.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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