



Modeling and analyzing the impact of on-street parking on traffic flow: a study of the main highway in Debre Markos Town, Ethiopia

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Abstract

Insufficient parking has emerged as a critical global transportation concern, particularly in central business districts, leading to congestion in urban transport networks with significant social, economic, and environmental implications. In Debre Markos city, the demand for taxis and travel is swiftly rising due to population growth. However, existing road facilities are inadequate, reducing road capacity, mobility, and exacerbating traffic congestion. On-street parking, encompassing parking occupancy, double parking, differences in peak hours between restaurant activity and passing traffic, lack of driver discipline, and the reduced maneuverability of older vehicles, all contribute to narrowing the available road width, thus impeding traffic flow. This study aims to bridge this knowledge gap by investigating the traffic congestion caused by on-street parking and its impacts on traffic flow. Study results indicate that on-street parking significantly reduces road capacity by 24.1% due to legal parking activities and an additional 25.89% due to illegal double parking. Removing on-street parking could enhance road capacity by 49.9% and reduce travel time by 36%. Additionally, the model reveals a strong relationship between on-street parking and the delay of vehicle movement toward parking locations, with each increase in parking occupancy decreasing average travel speed by 0.03 km/h. This study emphasizes the necessity for proactive policies to address parking issues and uphold urban street service levels amid increasing traffic demands. Local authorities can use the model as a guide for implementing parking prohibition policies, including utilizing dead-end roads for short-term parking, enhance enforcement of parking regulations, integrate parking management with urban planning, and implementing parking management measures to alleviate congestion.

Keywords On street parking · Parking demand and supply · Road capacity · Traffic flow · Occupancy

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Introduction

The urban transportation system is a vital engine for economic activities in urban societies. However, many cities are facing challenges due to increased road traffic and transport demand, leading to inefficiencies in the traffic system. On-street and off-street parking facilities in city centers are attractive options for drivers, but parking has become a major problem in urban areas worldwide, affecting both developed and developing countries. As stated by The Royal Automobile Club (RAC foundation 2004), nearly every car trip involves parking at the origin and destination, with cars spending more than 80% of the week parked. The availability of parking significantly influences travel mode and route choices, impacting the viability and competitiveness of commercial areas. The car-parking sector has always been highly important in terms of urban mobility since it is a fundamental element in achieving a high level of accessibility in city centers (Edinburgh Napier University 2008).

Parking not only contributes to the appearance of cities and suburbs but also affects traffic congestion, traffic operations, and urban street and transit systems. Many businesses and municipalities consider an adequate parking supply essential for their competitive growth and enhancing the urban environment (RAC foundation 2004). However, parking problems are becoming increasingly important in many metropolises, with the imbalance between parking supply and demand being a key issue (Weant and Levinson 1991).

To manage transport demand effectively and influence travel behavior, parking controls such as supply levels and charges should be part of comprehensive packages that also include measures to improve public transport, walking, and cycling. Coordinated approaches are needed, especially in areas competing with each other. On-street parking activities, including parking maneuvers, parking searches, double parking, and parked vehicle occupation of road space, affect road capacity and traffic flow. These activities interrupt adjacent traffic and can lead to lane blockages, inflow and outflow parking maneuvers, and illegal double-parked vehicles, creating bottlenecks. On the other hand, providing effective parking facilities is a fundamental part of the highway transportation mode. Areas with land used for business or commercial activities necessitate additional parking bays (Garber and Hoel 2009). However, the land in these high-density areas is expensive.

The allocation of on-street parking in central business districts (CBDs) affects road capacity and level of service, posing a common challenge for urban traffic engineers. Studies show that parked vehicles impact average travel speeds and other traffic operations, reducing street capacity. The capacity of streets was found to decrease due to lane blockage (Cao et al. 2016), inflow and outflow parking maneuvers (Sisiopiku 2001), and illegal double-parked vehicles, which can form bottlenecks (Kladeftras and Antoniou 2013). Parking and Ride (P&R) facilities, which allow users to park their vehicles on the outskirts of a city and continue their journey to the city center using public transport, are used to reduce on-street parking and traffic congestion (Macioszek and Kurek 2021). The likelihood of using P&R parking in Cracow is influenced by factors like age, years of driving experience, monthly income, and average daily trips. These facilities allow users to leave their vehicles on the outskirts of the city and use public transport to reach the city center, addressing on-street parking issues (Macioszek and Kurek 2020). However, in my study area, there is no park-and-ride system to alleviate on-street parking-related problems. Therefore, it is essential to provide park-and-ride facilities to recognize that enhancing on-street parking facilities can offer long-term solutions to alleviate congestion and parking issues in the studied area.

From my field observations, it is evident that there is insufficient enforcement of parking regulations, and the parking space markings are faded in certain sections of the road segment, resulting in problems with on-street parking that impact traffic flow in the city. This sentiment is shared by both local communities and business owners, who have expressed concerns about the challenges posed by inadequate parking management.

Considering the critical nature of this issue, it is essential for city administrations to tackle it by implementing stronger enforcement measures, maintaining on-street space markings, or providing adequate on-street parking alternatives. There is a clear readiness and willingness among stakeholders to collaborate towards finding solutions to this pressing issue. As researchers, I am committed to contributing to the resolution of these challenges, as I understand the diverse problems arising from the ineffective management of parking in this study area.

Moreover, traditionally, many cities have adopted standardized pricing strategies for parking, with fixed fees for parking meters throughout the day and consistent rates across different zones. However, this approach leads to issues: underpriced curb parking becomes congested, causing frustration for most drivers who waste time and fuel searching for a spot, while overpriced parking results in vacant spaces, leading to lost opportunities for businesses, unemployment, and reduced tax revenue for cities. To address these challenges, San Francisco has introduced an innovative solution by implementing a dynamic pricing system for on-street parking, as outlined by Pierce and Shoup in 2013. This system adjusts prices based on both the time of day and location. This innovative approach aligns with established theoretical principles for effectively pricing public services. However, in my research area, parking remains unpriced (unregulated), and enforcement is lacking, as per my observations and past experiences.

This research employs a combination of literature review and field study methodologies to gain insights into the current understanding and concerns regarding urban parking management. It aims to determine parking demand and supply, model the impact of on-street parking on traffic flow, and propose a more effective parking management program for the city.

The study was prompted by the escalating issues of traffic congestion and travel time delays in Debre Markos City, Ethiopia. Despite the significance of these issues, related studies have failed to adequately describe the root causes and specific contributing factors in Ethiopian cities. On-street parking activities are identified as a notable contributor to congestion. This research seeks to address these gaps by investigating parking demand and supply dynamics and examining the impact of on-street parking on traffic flow. Additionally, it aims to suggest mitigation measures and strategies to improve traffic management. The model developed in this study has the potential to serve as a valuable guideline for local authorities. Furthermore, the study emphasizes the necessity of proactive policies to tackle parking issues and uphold urban street service levels amid the escalating demands of traffic.

Overview of the study

Parking and its facility

Parking is a crucial element of every car trip, particularly in urban areas, as it is necessary for all vehicles when not in use. Numerous studies have explored parking systems

for various reasons, including mode choice, accessibility of locations, and network performance affected by traffic congestion and parking choices. Driver behavior is influenced by factors such as parking access, fees, walking distance to final destinations, and various socioeconomic characteristics (Pel et al. 2016).

Parking facilities are essential components of transportation systems (HOBBS 1984), especially road networks. Vehicles require parking areas at the end of their trips, which include facilities at office buildings, shopping centers, banks, universities, airports, train and bus stations, and hospitals in urban and suburban areas.

Failure to provide adequate parking infrastructure for expected demands or offering inappropriate roadside parking can lead to traffic congestion and reduced road capacity. Conversely, an excess of parking spaces can promote more car trips and ownership. Therefore, effective parking management is crucial for the economic efficiency of a facility (Ison and Mulley 2014).

Literature on parking management emphasizes the importance of implementing effective enforcement measures and parking regulations to address congestion and parking issues (Litman 2023). Weak enforcement of parking regulations can lead to on-street parking problems, as observed in various urban settings (Guerra and Cervero 2019).

Types of parking

Parking facilities can be categorized based on their location, layout, and payment terms, each offering unique advantages and disadvantages for various stakeholders in the transportation sector. Additionally, different types of parking have varying effects on nearby traffic. One way to classify parking is by its proximity to the roadside, distinguishing between on-street parking, located alongside roads, and off-street parking, situated away from the road. Thus, parking facilities are broadly classified as either on-street or off-street parking based on their location.

On-street parking

On-street parking refers to vehicles parked along the sides of the street itself, with designated bays provided on one or both sides of the road. It is crucial to carefully plan these facilities to ensure that parked cars do not disrupt the proper functioning of the road. Research conducted in China (Cao et al. 2016) indicates that the reduction in effective lane width caused by on-street parking significantly impacts road capacity and affects traffic flow in adjacent lanes.

Another study from China suggests that the characteristics of roadside parking bays, such as whether they are restricted, offer paid services, or are free, can also influence the traffic flow on nearby roads (Yan-ling et al. 2015).

On-street parking spaces are typically marked either as individual bays or as sections of the street where parking is permitted. The number of bays can be explicitly counted, while for sections where parking is allowed, an estimate of 5–7 m of curb space per parking space is reasonable. Slinn, Matthews, and Gues determined in their study that 5 m is a suitable figure for calculating parking spaces based on empirical observations from various surveys (Slinn et al. 2005).

Studies have shown that inadequate parking management can have significant impacts on urban mobility and economic vitality. For instance, businesses reliant on on-street parking may face challenges in attracting customers if parking spaces are unavailable or

improperly regulated (Pierce and Shoup 2013). This aligns with the concerns voiced by both local communities and business owners in our research area regarding the challenges posed by insufficient parking management and enforcement. Given the critical nature of this problem, city administrations must explore various solutions to improve parking management and enforcement. Enhancing enforcement measures, providing sufficient on-street parking, or implementing alternative strategies such as park-and-ride systems are potential approaches to address these challenges (Jiang et al. 2021). Engaging stakeholders, including the police and business owners, in discussions about parking regulations and enforcement strategies is essential to develop effective and sustainable solutions (Pierce and Shoup 2013; Guerra and Cervero 2019).

Off-street parking

In many urban areas, certain designated zones are reserved exclusively for parking, often situated away from main traffic routes. This type of parking is known as off-street parking and includes facilities such as surface lots and parking garages. These facilities can be owned either privately or by the public sector. Public off-street parking refers to lots owned or operated by either private entities or the government, where drivers can park their vehicles after adhering to regulations such as payment of a fee and adhering to maximum stay limits. Unlike on-street parking, public off-street parking facilities are not located on public roads and are typically accessible to anyone seeking to park their vehicle there.

A shortage of off-street parking facilities and a tendency for vehicles to park near their destinations contribute to high on-street parking demand. Additionally, factors such as vehicle ownership rates and inadequate public transit options further exacerbate this demand. These factors collectively lead to reduced roadway widths, lower travel speeds, and congestion, all of which contribute to a shortage of available parking spaces (Sen et al. 2016).

On the other hand, private off-street parking is associated with specific buildings or land use. For example, this could include parking for a shopping center or an office building. In theory, only individuals associated with the particular building or land use should be allowed to use the parking facilities, and the landowner has control over this access within the relevant legal framework.

Parking demand surveys

Parking demand is related to different characteristics of the surrounding roads, including land use, parking price, parking space supply, car ownership, and mode choice. These factors are critical for calculating the future parking demand in an area.

A number of models have been used to determine different parking demand levels under different conditions. Wong et al. (2000) developed a parking demand model for Hong Kong city to calculate the future parking demand of the city. This model was developed by assuming a linear and additive relationship between off-street parking and the land use variable. Another study developed a parking demand model using linear regression analysis in the SPSS tool (Aderamo and Salau 2013). Recently, in 2016, they developed a parking demand model that uses the parameters of an average number of 4-wheelers owned, an average duration of parking, and mode choice. Then, they estimated the parking demand of the Kolkata metropolitan city and compared it with the existing parking supply (Sen et al. 2016).

The parking demand refers to the number of vehicles seeking parking in a specific area within a given time frame. This demand can be assessed through direct field observations, where the number of parked vehicles, their locations, durations, vehicle types, and other relevant parameters are recorded. Subsequently, this data is used to calculate metrics such as parking occupancy, turnover, and duration (Garber and Hoel 2009).

Parking demand is influenced by various factors related to the surrounding area, including land use, parking pricing, available parking spaces, vehicle ownership rates, and transportation mode choices. Understanding these factors is crucial for predicting future parking demands in a given area.

Several models have been developed to estimate parking demand under different conditions. For instance, Wong et al. (2000) created a parking demand model for Hong Kong, assuming a linear relationship between off-street parking and land use variables. Another study utilized linear regression analysis in the SPSS tool to develop a parking demand model (Aderamo and Salau 2013). In 2016, a parking demand model was developed for Kolkata using parameters such as average number of owned 4-wheelers, average parking duration, and transportation mode choices. This model was used to estimate parking demand in Kolkata and compare it with existing parking supply (Ahmed et al. 2016).

On-street parking and road capacity

Several studies have investigated the impact of on-street parking on road capacity. According to the American Association of State Highway and Transportation Officials (AASHTO), removing curbside parking can increase the road capacity of four- to six-lane arterial roads by 50–80% (AASHTO 2001). Additionally, research by Weant and Leverson (as cited in Wijayaratra 2015) indicates that removing roadside parking on a four-lane road doubles the capacity, while eliminating on-street parking on a six-lane road leads to a 67% capacity gain. These findings highlight the direct impact of on-street parking on road capacity, primarily due to the loss of traffic lanes when on-street parking is allowed. Another recent study (Portilla et al. 2011), used microsimulation modeling to demonstrate that the road capacity of remaining lanes decreased significantly, by up to 16%, due to 30 parking maneuvers per hour. Illegal double-parked vehicles, which park for only 15 min, were found to imply a 14% reduction in hourly flow (Portilla et al. 2011).

In a specific scenario, such as a two-lane one-way road with parallel on-street parking in a business district, there exists a notable relationship between parking turnover and the delay of through traffic flow moving toward the parking location. Moreover, this relationship is affected by the volume of through traffic (Thohirinl et al. 2019).

On-street parking and traffic congestion

Traffic congestion is closely linked to road capacity and the volume of traffic during peak hours. Numerous studies have demonstrated that on-street parking significantly contributes to urban traffic congestion. A study conducted in the United Kingdom (Yousif and Purnawan 1999), revealed that parking maneuvers create temporary bottlenecks in traffic flow, leading to operational issues like congestion, delays, and potentially, accidents. An empirical study (Andrew et al. 2014), identified inadequate parking space as the primary cause of traffic congestion in a Nigerian city. The analysis showed that 53.7% of respondents cited insufficient parking spaces, resulting in increased parking searches and illegal parking, as the main factors contributing to traffic congestion.

Managing travel demand and increasing road capacity are potential strategies for addressing congestion. However, implementing effective travel demand management measures is challenging, unpopular, and politically sensitive (Gärling and Schuitema 2007). Similarly, increasing road capacity has become expensive, time-consuming, and often unfeasible in many cities due to limited space for road construction.

On-street parking and travel speed

Traffic speeds are becoming a significant concern in central business district (CBD) areas, with several studies indicating that increased on-street parking tends to reduce vehicle capacity and travel speeds. Previous research has clearly established the impact of on-street parking on traffic speed and other operational aspects.

Studies have shown that, on average, there is about a 10 km/h reduction in mean speeds between situations of empty and full on-street parking. This effect is even more pronounced in 85th percentile speeds, with the degree of speed reduction varying only slightly based on road widths (Koorey and Praburam 2015).

Marshal, Garrick, and Hansen's study (Wesley et al. 2008) concluded that for streets with significant on-street parking, the parking environment significantly influences drivers' speed choice. Vehicles with on-street parking experience a decrease in free-flow speed by approximately 2.3 mph (3.7 kph) compared to those without on-street parking. Another study (Kladeftras and Antoniou 2013), used sensitivity analysis to examine the impacts of illegal double parking on average speed, delay, and stop time. The findings indicated that all traffic indicators improved when double parking was minimized. Reducing double parking led to speed increases of approximately 10–15% and decreases in delay and stop times of approximately 15% and 20%, respectively. The study also suggested that even greater improvements could be achieved by eliminating double parking, with potential increases in average speed of up to 44% and decreases in delay and stop time of up to 33% and 47%, respectively.

On-street parking and land use

Parking studies are conducted to assess various aspects of the transportation network, such as the necessary right of way near specific land uses, the maximum allowable traffic volume on adjacent streets, and the appropriate size of parking facilities for different types of land use. The amount of parking available can impact the road network, potentially reducing its operational level of service. Conversely, insufficient off-street parking for specific land uses can have negative economic consequences (Al-Sahili and Hamadneh 2016).

Furthermore, Sahili and Hamadneh (2016) highlight in their study that trip and parking generation play a role in shaping urban areas and assist decision-makers in urban planning.

Modeling of on-street parking

Macroscopic modeling

Macroscopic modeling refers to a mathematical traffic model that examines the connections among traffic flow characteristics, such as density, flow, and the average speed of a traffic stream. Understanding these relationships is crucial for predicting highway capacity

during the design phase. Over the years, various models have been developed to illustrate the relationships between speed (v), flow (q), and density (k). Commonly used models in different studies include the linear model, the Greenshields model, the Greenberg model, and the Underwood model. These models help determine specific characteristics like the speed and density at which maximum flow occurs, as well as the jam density of a facility.

Micro simulation modeling

Leung and Wijayaratna created a microsimulation model in AIMSUN to replicate an arterial road in Sydney, featuring 30 parking spaces on each side of the curb lanes. Their study explored four distinct parking policy scenarios: no parking, unrestricted parking, 1-h parking restrictions with reverse parking maneuvers, and 1-h parking restrictions with front-in parking only. The findings suggest that the maximum impact of parking is a viable outcome in heavily used parking zones (Leung and Wijayaratna 2015). Another study in China (Lin et al. 2013) utilized VISSIM traffic simulation software to assess various traffic management scenarios, determining the optimal measures before implementation. VISSIM, widely employed microscopic simulation software, is effective for evaluating traffic conditions.

Additionally, researchers have utilized microsimulation modeling outcomes to verify travel-time results from various analytical models. A study in Cantabria, Spain, employed a microsimulation model to validate the increase in travel time caused by on-street parking maneuvers and improperly parked vehicles, as identified in the $M/M/\infty$ queuing model (Portilla et al. 2011).

Research methodology

Study area

This research was conducted on a specific major highway corridor situated in the heart of the Debre Markos Metropolitan City, Ethiopia. Geographically, Debre Markos town is positioned at approximately $10^{\circ} 20' N$ latitude and $37^{\circ} 43' E$ longitude, with an elevation of 2446 m. It is situated around 300 km away from Addis Ababa. The central area of the city covers an estimated 21.53 square kilometers. Its strategic location offers various advantages, including abundant water resources, favorable topography, and a pleasant climate (Institute, Federal Urban Planning 2013).

Study design (research frame)

In a general scope, this study aims to analyze and model the effects of on-street parking on traffic flow characteristics along specific road corridors in Debre Markos town. It seeks to conduct a thorough examination of the relationship between on-street parking and traffic flow on these roads. Data, both secondary and primary, were gathered from multiple sources. This included information on traffic volume and parking occupancy, parking accumulation, traffic flow rates and speeds, parking turnover rates, travel times, duration of double parking incidents, vehicle parking lengths, and road widths.

Sample size and sampling procedure

Parking survey data and traffic flow data were collected and analyzed. The parking survey data included information on parking accumulation, parking inventory, vehicle lengths, parking demand, double parking incidents, parking maneuvering times, and road widths. Traffic flow data analysis involved examining traffic flow rates, travel times, and average travel speeds. Both descriptive and inferential statistical analyses were employed to understand the distribution of on-street parking parameters over the study period.

Research methods

The research utilized both primary and secondary data sources. Secondary data, obtained from various city stakeholders, included a city road map, orthophoto images, and the average annual daily traffic (AADT) of the study segments. Primary data, collected through direct field surveys, included parking inventory, parking demand, parking maneuver times, traffic flow rates, average travel speeds, double parking durations, vehicle lengths, travel times, and road widths.

Research materials

Various tools and instruments were employed for field data collection in this study, tailored to the specific data types and measurements required. A measuring tape was utilized to measure segment lengths along the study corridor. This tape, combined with a stopwatch, facilitated the calculation of average vehicle speeds. Additionally, a stopwatch was used to measure driver maneuvering times and travel times using the test vehicle method. Video recording was employed to capture traffic flow at the study location, aiding in traffic flow and average speed calculations. Several software applications were utilized for data analysis. Microsoft Excel was used for basic calculations and table formatting. ArcGIS was used to visualize different geographical features in the study area. AutoCAD was employed for simple sketches to illustrate various properties. Statistical analysis was conducted using SPSS software, and graphs and histograms were generated using Sigma plots. Finally, documentation was completed using Microsoft Word.

Details of the data collection

Various types of input data were collected for this study. These data were subjected to both descriptive and inferential statistical analyses using SPSS software. This analysis aimed to derive significant findings and develop macroscopic traffic models to understand the impact of on-street parking at the study locations.

Analysis, results, discussion, and interpretation

This study aimed to assess the effectiveness of on-street parking services and quantify the traffic disruption caused by on-street parking activities. The research findings are presented, analyzed, and discussed using empirical, statistical, graphical, and tabular methods. Each subtopic's discussion considers the implications of the results in light of relevant research.

This section provides a comprehensive analysis of the collected data, focusing on the impact of on-street parking on traffic flow, and discusses the findings in the context of existing literature and local conditions.

In Debre Markos city, the majority of parking spaces are located on the sides of streets, with most roads serving as parking areas unless restricted. An extensive inventory of parking locations classified the curbside areas into three categories:

- The allowable parking locations were found to be within 601.9 m of the roadside.
- No parking locations due to crossroads were found to cover 134.8 m of the roadside.
- No parking locations due to cross walking were found to cover 117 m of the roadside.

These sites were further classified into segments A and B, with the left side of the roadside designated as "A" and the right side as "B" (Table 1).

The selected segment clearly shows distinct parking characteristics, with most road-sides being used for parking except for walkways and crossroads. Field observations revealed that drivers frequently parked their vehicles illegally on crosswalks and parts of crossroads when other spaces were occupied. Although the Highway Capacity Manual (HCM) (Transportation Research Board, N. R. C. 2000) specifies a 16-m length of parking-free space on approach roads to intersections for site distance and intersection capacity reasons, this regulation is often disregarded by city drivers due to lax enforcement by regulatory bodies like the traffic police. However, parking in these locations significantly impacts road safety and capacity.

Table 1 Summary of the parking characteristics of the study sites

| Site code | Total length(m) | Parking restriction due to cross road (m) | Parking restriction due to cross walk(m) | Parking allowable length (m) |
|-----------|-----------------|---|--|------------------------------|
| 1A | 104.38 | 16.4 | 8.6 | 79.38 |
| 1B | 88.76 | 9.6 | 8.6 | 70.56 |
| 2A | 124.98 | 30.1 | 15.5 | 79.38 |
| 2B | 97.94 | 22.3 | 13.9 | 61.74 |
| 3A | 101.76 | 18.1 | 9.2 | 74.46 |
| 3B | 108.65 | 7.8 | 24.4 | 76.45 |
| 4A | 124 | 19.3 | 18.6 | 86.1 |
| 4B | 102.42 | 11.2 | 18.2 | 73.02 |
| SUM | 852.89 | 134.8 | 117 | 601.09 |

Table 2 Statically measure for field observation of vehicles parking length determination

| No | Statically measures | Symbol | Unit | Result |
|----|---------------------|---|--------|-------------------------------|
| 1 | Sample size | N | Number | 126 |
| 2 | Mean | \bar{x} | Meter | 7.21 |
| 3 | Standard deviation | S | Meter | 1.39 |
| 4 | 85% value | $\times 85\%$ | Meter | 8.82 |
| 5 | 90% value | $\times 90\%$ | Meter | 9.12 |
| 6 | 95% value | $\times 95\%$ | Meter | 9.38 |
| 7 | Confident interval | $\bar{x} - z\alpha/2 * s/\sqrt{n}$ | Meter | 6.96 |
| 8 | | $\bar{x} + z\alpha/2 * s/\sqrt{n}$ | Meter | 7.36 |
| 9 | | $\bar{x} - z\alpha/2 * s/\sqrt{n} \leq \bar{x} \leq \bar{x} + z\alpha/2 * s/\sqrt{n}$ | Meter | $6.96 \leq \bar{x} \leq 7.36$ |

Determination of standard parking length

A standard parking length serves as a guideline for designing parking stalls to accommodate the vehicle population requiring parking spaces. The actual parking space consumption of vehicles in the city was determined from field investigation, considering 85% of the length of the collected data (Table 2).

To assess the effectiveness of on-street parking in terms of roadside length usage, it is necessary to determine the dimensions of the design vehicle for parking. Field measurements of vehicle lengths indicate that vehicles of varying lengths are parked with different frequencies along the selected corridor. The design vehicle length is then calculated by adding a maneuvering length of 1.2 m–85% of the length of the design vehicle, as follows (Table 3):

The frequency distribution graph shown below was used to determine the different length percentiles.

Figure 1 aims to illustrate the disparity between the calculated parking length, considering the 85% design vehicle length with an additional maneuvering space, and the actual length occupied by parked vehicles based on field observations.

Table 3 Statically measure for vehicle length distribution

| No | Statically measures | Symbol | Unit | Result |
|----|---------------------|---|--------|-------------------------------|
| 1 | Sample size | N | Number | 126 |
| 2 | Mean | \bar{x} | Meter | 4.04 |
| 3 | Standard deviation | S | Meter | 0.651 |
| 4 | 85% value | $\times 85\%$ | Meter | 4.69 |
| 5 | 90% value | $\times 90\%$ | Meter | 4.86 |
| 6 | 95% value | $\times 95\%$ | Meter | 5.03 |
| 7 | Confident interval | $\bar{x} - z\alpha/2 * s/\sqrt{n}$ | Meter | 4.01 |
| 8 | | $\bar{x} + z\alpha/2 * s/\sqrt{n}$ | Meter | 4.11 |
| 9 | | $\bar{x} - z\alpha/2 * s/\sqrt{n} \leq \bar{x} \leq \bar{x} + z\alpha/2 * s/\sqrt{n}$ | Meter | $4.01 \leq \bar{x} \leq 4.11$ |

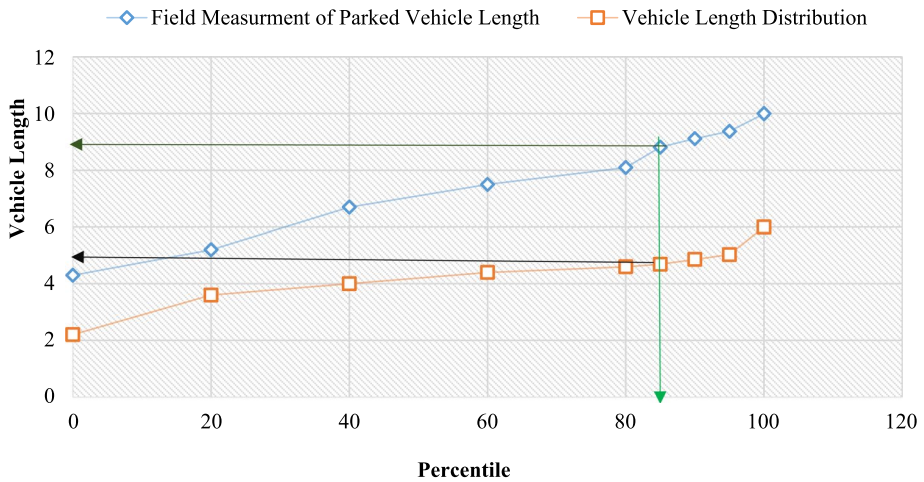


Fig. 1 Parking length and vehicle length at different percentiles

In this context, ‘percentile’ refers to a statistical measure indicating the length of a vehicle used for parking purposes, specifically determined as 85% of the vehicle length.

The discrepancy arises from various factors such as illegal parking activities, inefficiency, and lack of discipline among drivers in parking, as well as the reduced maneuverability of older vehicles. These factors collectively contribute to parked vehicles occupying a significantly larger roadside space (8.84 m) compared to the standard calculated parking length (5.91 m) based on the city’s vehicle population.

Therefore, the intention of Fig. 1 is to visually depict this notable difference between the calculated parking length and the actual space occupied by parked vehicles, highlighting the challenges and deviations from standard parking practices caused by various factors influencing driver behavior and vehicle characteristics.

Estimation of on-street parking capacity

The initial capacity for on-street parking is calculated by determining the number of parking spaces within each area. This is done by dividing the length of the street where parking is permitted by the standard length of a parking space for vehicles.

$$N_{\text{standard}} = \frac{L - C_w - C_r}{A} \tag{1}$$

where: L- Total length, N-Number of parking spaces, C_w- Width of crosswalks, C_r- Width of the crossroad, A- Standard parking length of a vehicle.

The standard length of a vehicle was established by measuring the parking space occupied by a vehicle and analyzing it empirically to determine the 85% parking length of vehicles in the city (Brčić et al. 2012). To account for the varying lengths of vehicles on the road, the standard vehicle parking length can be calculated using the weighted mean as shown below (Table 4).

Table 4 Estimation of on-street parking capacity

| Site code | Total length(m) | Total parking restriction (m) | Parking allowable length (m) | Number of space as per local parking behavior | Number of space as per standard vehicle length |
|-----------|-----------------|-------------------------------|------------------------------|---|--|
| 1A | 104.38 | 25 | 79.38 | 9 | 13 |
| 1B | 88.76 | 18.2 | 70.56 | 8 | 12 |
| 2A | 124.98 | 45.6 | 79.38 | 9 | 13 |
| 2B | 97.94 | 36.2 | 61.74 | 7 | 10 |
| 3A | 101.76 | 27.3 | 74.46 | 8 | 12 |
| 3B | 108.65 | 32.2 | 76.45 | 9 | 13 |
| 4A | 124 | 37.9 | 86.1 | 10 | 14 |
| 4B | 102.42 | 29.4 | 73.02 | 8 | 12 |
| SUM | 852.89 | 251.8 | 601.09 | 68 | 99 |

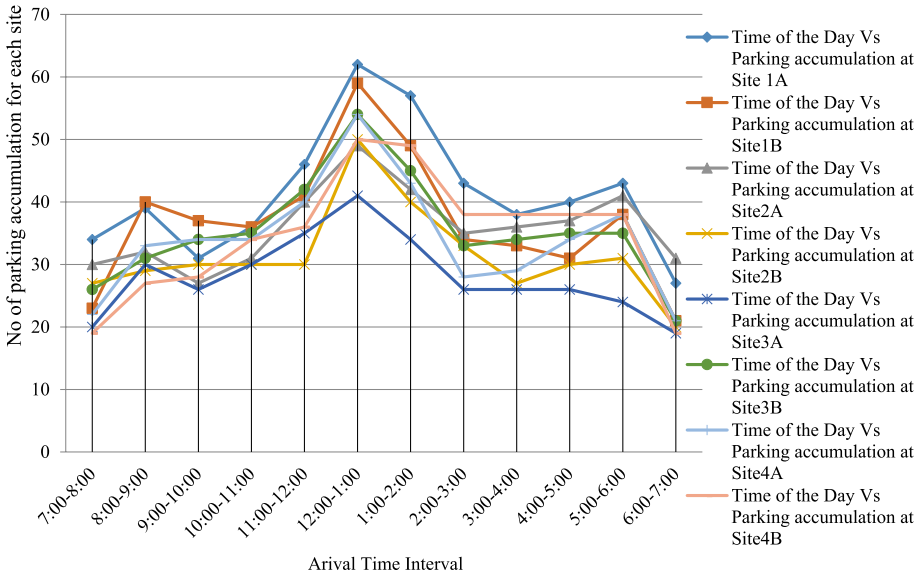


Fig. 2 Parking accumulation

$$A = \frac{(4.69 + 1.2) * 0.85 + (6.1 + 1.2) * 0.15}{0.85 + 0.15} = 6.101$$

The table above calculates the estimated on-street parking capacity for two scenarios. Based on local drivers’ parking behavior, there are 68 available parking spaces. However, this number increases to 99 if drivers adhere to the parking length determined by the city’s design vehicle. Therefore, efforts to modify drivers’ parking behavior could add additional (31.3%) roadside parking spaces to meet parking demand.

Determination of the parking demand accumulation

The license plate method was employed to assess the rate of parking demand at the chosen study site. Figure 2 below illustrates the accumulation data for all on-street parking locations.

In this study, 15-min and hourly intervals were utilized to ensure data quality, based on the experience of high business activities in the city and my field observations. Parking demand data were surveyed from 7:00 a.m. to 7:00 p.m. on both Tuesday and Saturday. A comparison of the data revealed that Saturday had the highest demand, so Saturday's data were used for the analysis.

All vehicles parked in the study area were counted hourly on average over 2 days (Tuesday and Saturday) from 7:00 a.m. to 7:00 p.m. The highest demand volume was recorded from 7:00 a.m. to 7:00 p.m., with the peak demand occurring between 12:00 p.m. and 1:00 p.m. Conversely, the minimum demand volume was recorded between 6:00 p.m. and 7:00 p.m.

The parking accumulation graph (Fig. 2) presents the total number of vehicles parked in the area at any given time. The trends for the eight study sites were similar, with vehicle accumulation decreasing in the early morning, increasing to peak accumulation, decreasing until lunchtime, and then gradually rising until late afternoon.

Comparing parking demand across sites, site 1A had the highest demand, with 62 vehicles during peak hours. Field observations indicated a high number of double parking activities at this site, likely due to the imbalance between parking demand and supply, leading to illegal behaviors such as double parking.

As the study results on Saturdays in the study area indicate, parking demand is primarily driven by restaurant activity, particularly during lunchtime, which contrasts with lower passing traffic during this 'off-peak' period. This discrepancy is due to several factors, including differences in peak hours between restaurant activity and passing traffic, localized concentrations of dining establishments leading to specific spikes in parking demand, the behavior of restaurant-goers affecting parking patterns, economic considerations influencing dining out during off-peak traffic times, and the urban layout and design impacting parking demand patterns. Understanding these dynamics can help optimize parking management strategies.

Parking turnover

Parking turnover is calculated by dividing the number of vehicles parked for a specific duration by the number of available parking bays. It represents the number of vehicles occupying a parking space within a given hour. This is calculated as follows:

$$\text{Parking Turnover} = \frac{\text{Number of Different Car Park}}{\text{No.of Bays Available}} \quad (2)$$

$$\text{Parking Turnover} = \frac{223}{9} = \frac{27\text{Vehicle}}{12\text{hr}} = 2.25 \text{ veh/h}$$

The graph in Fig. 3 illustrates the distribution of parking turnover for site 1A throughout the day. The highest turnover, reaching 3.16 vehicles, occurred from 12:00 p.m. to 1:00 p.m., indicating that each parking space accommodated an average of 3.16 vehicles per hour at this time period. The parking turnover for the other segments is outlined in Table 5.

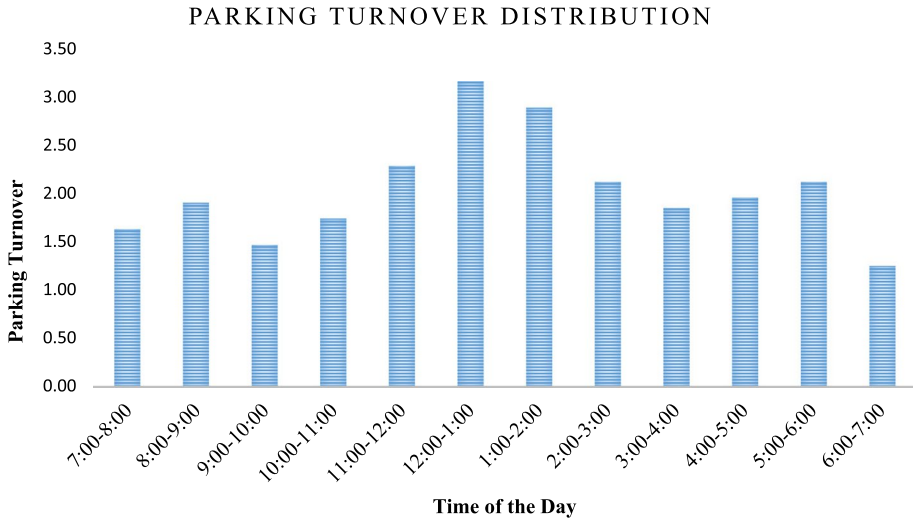


Fig. 3 Sample parking turnover distribution for site 1A

A parking turnover rate of 2.25 vehicles per hour (veh/h) is generally considered quite low for urban areas, especially for on-street parking. In urban settings, higher turnover rates are typically desired to accommodate the high demand for parking spaces and to promote the efficient use of limited parking resources.

A rate of 2.25 veh/h suggests that parking spaces are not being utilized very frequently, which could indicate inefficiencies in the parking management system. In such cases, there may be opportunities to improve the parking situation, such as by implementing pricing strategies, adjusting parking regulations, or improving the availability and visibility of parking spaces.

Parking occupancy

Parking occupancy refers to the proportion of occupied parking bays during a specific time period compared to the total available spaces. It offers a comprehensive indication of the efficiency of parking space utilization. This can be calculated as follows:

$$\text{Parking Occupancy} = \frac{\text{Number of Occupied Spaces}}{\text{No. of Bays Available (Total Number of Spaces)}} * 100 \quad (3)$$

The parking accumulation of segment 1A for a time interval of 6:45–7:00 am can be calculated as follows:

$$\text{Parking Occupancy} = \frac{17}{9} * 100 = 189\%$$

With the same approach, the parking occupancy for each time interval is computed in the above table. The average segment parking occupancy is calculated as follows:

Table 5 Summary of parking demand

| Site code | No of parking spaces as per local behavior | Parking volume | Parking turnover per day | Parking turnover per hour | Average parking occupancy (%) | Parking duration in minutes | Maximum parking duration (hr) |
|-----------|--|----------------|--------------------------|---------------------------|-------------------------------|-----------------------------|-------------------------------|
| 1A | 9.00 | 243.00 | 27.00 | 2.25 | 117.26 | 30.6 | 2.6 |
| 1B | 8.00 | 206.00 | 25.75 | 2.15 | 117.55 | 32.2 | 2.7 |
| 2A | 9.00 | 196.00 | 21.78 | 1.81 | 101.89 | 33.0 | 2.8 |
| 2B | 7.00 | 160.00 | 22.86 | 1.90 | 114.59 | 35.3 | 3.0 |
| 3A | 8.00 | 201.00 | 25.13 | 2.09 | 89.63 | 25.2 | 2.1 |
| 3B | 9.00 | 211.00 | 23.44 | 1.95 | 100.47 | 30.2 | 2.5 |
| 4A | 10.00 | 189.00 | 18.90 | 1.58 | 87.23 | 32.5 | 2.7 |
| 4B | 8.00 | 168.00 | 21.00 | 1.75 | 110.11 | 37.0 | 3.1 |
| AV | | | | 1.94 | 104.84 | 32.0 | 2.8 |

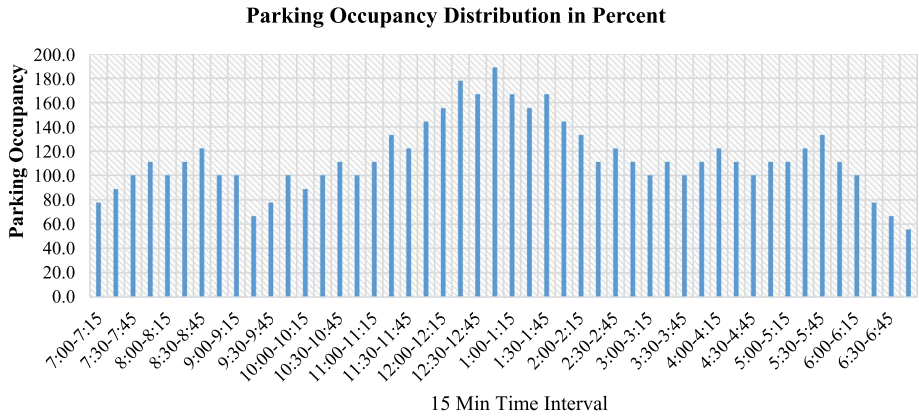


Fig. 4 Sample parking occupancy distribution for site 1A

$$\text{Average Parking Occupancy} = \frac{\sum_{k=1}^{48} \text{Occu}}{47} = \frac{55.11}{47} = 117.26\%$$

The results indicate that parking space occupancy exceeds 85% for a majority of the time. In instances where parking spaces are insufficient, drivers tend to park illegally, such as parallel to already parked cars, on crossroads, or on crosswalks, and as I saw the trend, at this time the local administration and local business man communities does not interfere the this activities. To mitigate double parking on the city’s main roads, the city administration should consider measures to increase parking supply, ensuring that parking occupancy remains below 85%. Additionally, enforcing traffic rules and regulations should be improved. The parking occupancy for the remaining segments is calculated as presented in Table 5 below (Fig. 4).

Parking duration

Parking duration refers to the average length of time a parking space is occupied by a vehicle. It is calculated by multiplying the sum of the accumulations for each time interval by the time interval, then dividing by the total parking volume.

$$\text{Parking Duration} = \frac{\text{Parking Load}}{\text{Parking Volume}} = \frac{\text{Sum of Accum} * \text{Time Interval}}{\text{Parking Volume}} \tag{4}$$

$$\text{Parking Duration} = \frac{496 * 15}{243} = 30.6 \text{Minutes/Vehicles}$$

The shortest duration a vehicle was parked at any site was 15 min. However, the maximum duration varied by site; for instance, at site 1A, vehicles were parked for a maximum of 30.6 min each. The calculation provided above is specific to segment 1A; results for the other segments are detailed in Table 5 below.

Table 6 Summary of double parking (illegally parked) duration and frequency

| Segment code | Average duration (Minute) | Frequency |
|--------------|---------------------------|-----------|
| 1A | 8.6 | 18 |
| 2A | 9.8 | 22 |
| 3B | 11.23 | 24 |
| 3A | 9.85 | 20 |

Double parking (illegally parking)

Double parking refers to a vehicle parking on the roadside next to another vehicle already parked at the curb. This is typically caused by a shortage of available on-street parking spaces (Gao and Ozbay 2016).

The study examined peak parking demand to understand the impact of double parking on traffic flow. For example, in segment 2A of the sample, there were 22 instances of double parking (illegally parked), with an average duration of 9.8 min per hour. This indicates that during peak parking hours, the lane next to the parking lane is obstructed by illegally parked vehicles. The effect of double parking on traffic flow depends on both its frequency and duration. The more frequent and longer the double parking is the greater the obstruction to the road. This obstruction directly affects travel time and average speed, with the severity correlating to the frequency and duration of these incidents. A summary of the double parking duration and frequency can be found in the table below (Table 6).

When the available parking supply is insufficient for the given parking demand, the drivers are forced to park their vehicles on the side of other parked vehicles (double parking) by blocking the adjacent lane of the road segment. Under these conditions, the capacity of the road is reduced by one lane for the same traffic demand. This scenario creates a bottleneck in traffic facilities.

Traffic analysis

A directional traffic volume analysis was carried out using traffic flow data obtained from the Debre Markos Traffic and Transportation Administration Office as secondary data. The data was collected at 15-min intervals from 7:00 a.m. to 7:00 p.m. The traffic flow distribution throughout the day was examined by dividing the study segments into four sections: FM hotel to Tilk hotel, Total Madeya to Shebel hotel, Starr business group center to off-street parking entrance, and Telecommunication office to Abma hotel. The 15-min and hourly traffic flow distributions for these sites are outlined in the Fig. 5 below.

The traffic flow data depicted above were gathered at intervals corresponding to varying levels of parking demand, including lower, medium, and higher demand hours. This method was crucial for understanding how on-street parking affects road performance, including average speed and travel time. The chart displays the peak 15-min traffic flow on the site, reaching up to 104 pcu/15 min. Traffic flow was observed to be lower during times of lower parking demand and higher during medium parking demand periods. During hours of higher parking demand, traffic flow was slightly lower than the peak traffic demand.



Fig. 5 Traffic flow distribution at each study site

During the morning peak hour, the study segment experienced a traffic flow of 390 passenger cars per hour (pc/h), which then decreased until lunchtime. Following lunch, traffic flow began to increase again, peaking at 329 pc/h in the afternoon.

Video recordings revealed several factors that interrupted traffic flow, particularly during higher parking demand hours, leading to a stop-start flow pattern. The increased parking demand had a noticeable impact on both the average speed and travel time of vehicles.

A detailed traffic survey was subsequently conducted at the selected study sites during specific time ranges, chosen based on the level of parking demand at each site.

- Lower parking demand 6:00 pm –7:00 pm (average occupancy of 65.97%)
- Middle parking demand hour 5:00 pm–6:00 pm (average occupancy of 106.1%)
- Higher parking demand 12:00 pm–1:00 pm (average occupancy of 155.08%)

Road capacity reduction

The capacity of the road segment was significantly impacted by parked vehicles on the street sides. These segments include a 2.4-m auxiliary lane to accommodate parked vehicles. A comparison was conducted between the road segment capacities under different conditions: when legal on-street parking was permitted, when on-street parking was prohibited, and when double parking occurred. The maximum service flow rate was calculated as the product of the capacity under ideal conditions and the maximum volume-to-capacity ratio for Level of Service E.

$$\text{Capacity} = C_{ideal} * N * \frac{V}{c} * F_w * FH_v * F_p * PHF \tag{5}$$

where:— C_{ideal} the base saturation flow rate, N -Number of lanes,— $\frac{V}{c}$ volume to capacity ratio, F_w – lane width adjustment factor, FH_v —the heavy vehicle adjustment factor, F_p - the parking adjustment factor, and— PHF Peak-hour factor.

The base (ideal) saturation flow rate for urban streets, as specified in the HCM manual, is 1,900 pc/h/ln. The volume-to-capacity ratio for Level of Service E is 1. The lane width adjustment factor is calculated following the procedure outlined in the HCM (2010). For a lane width (W) of 3.6 m, the lane width adjustment factor can be determined as follows:

$$F_w = 1 + \frac{(W - 3.6)}{9} \tag{6}$$

$$F_w = 1 + \frac{(3.6 - 3.6)}{9} = 1$$

According to a study conducted by Girum Tamene for Ethiopian conditions (Tamene 2016), the suggested passenger car equivalent for terrain at a general level and grades not exceeding 2% were adopted. For trucks and buses, the ET value was set at 2.5. The percentage of trucks and buses was then calculated from the traffic flow data for each site. For site 1A, trucks and buses accounted for 1.3% of the area, leading to the heavy vehicle adjustment factor expressed as follows:

$$FH_v = \frac{1}{1 + PH_v(ET - 1)} \tag{7}$$

$$FH_v = \frac{1}{1 + 0.013(2.5 - 1)} = 0.98$$

The parking adjustment factor was computed following the HCM (2010) procedure. For site 1A, with 38 parking maneuvers per hour based on the parking demand data, the parking adjustment factor is determined as follows:

$$F_p = \frac{N - 0.1 - \left(18 * \frac{N_m}{3600}\right)}{N} \geq 0.05 \tag{8}$$

$$F_p = \frac{2 - 0.1 - (18 * \frac{38}{3600})}{2} = 0.4$$

Table 7 Capacity calculation for site 1A

| Factors | Scenario 1 2-travel lanes | Scenario 2 2-travel lanes | Scenario 3 Medial lane |
|-----------------|------------------------------|------------------------------|---------------------------|
| Lane width | 3.6 | 3.6 | 3.6 |
| Number of lane | 2 | 2 | 1 |
| C ideal | 1900 | 1900 | 1900 |
| V/C | 1 | 1 | 1 |
| FW | 1 | 1 | 1 |
| FHv | 0.980 | 0.980 | 0.980 |
| F _p | 1 | 0.400 | 1 |
| PHF | 0.947 | 0.947 | 0.947 |
| Capacity (pc/h) | 3525 | 2676 | 1763 |

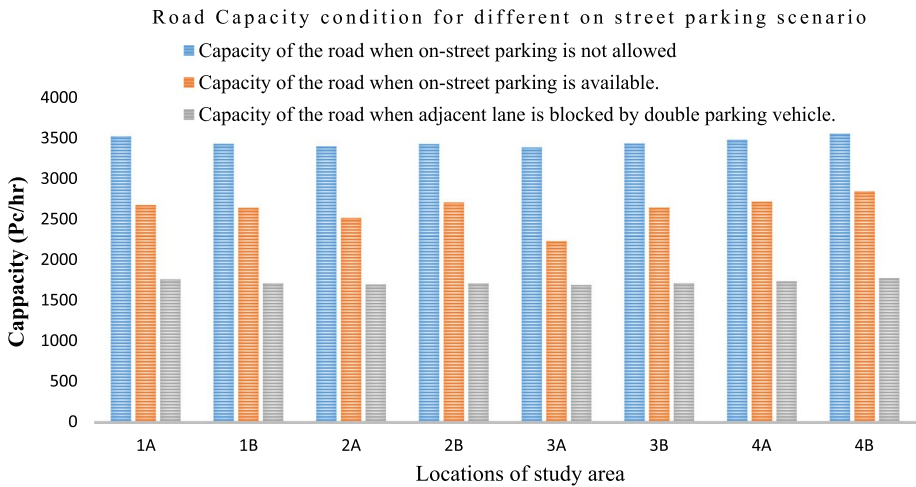


Fig. 6 Road capacity estimation for different on street parking scenario

The Peak-hour factor, which is the ratio of the hourly volume to the peak 15-min flow (V_{15}), increased to an hourly value; for site 1A, the following computation was used:

$$PHF = \frac{V}{4 * V_{15}} \tag{9}$$

$$PHF = \frac{382}{4 * 101} = 0.95$$

Therefore, from the above computed parameters, we can calculate the capacity of the road in different scenarios using manual HCM procedures. For scenario 1, for the two travel lanes, the capacity was calculated as:

$$Capacity = C_{ideal} * N * \frac{V}{c} * F_w * F_{Hv} * F_p * PHF \tag{10}$$

$$\text{Capacity} = 1900 * 2 * 1 * 1 * 0.98 * 1 * 0.95 = 3538 \text{ Pc/h}$$

The capacities of the roads in the three different scenarios are summarized as follows:

- *Scenario 1* Road capacity when on-street parking is not allowed.
- *Scenario 2* Road capacity when on-street parking is available.
- *Scenario 3* Capacity of the road when the adjacent lane is blocked by a double parking vehicle (Table 7).

The same procedure was used to compute the theoretical capacity of roads at each site, as summarized in the histogram below (Fig. 6).

The results of this study clearly indicate that on-street parking significantly diminishes road capacity. Three scenarios were evaluated: absence of parking, legal roadside parking, and double parking. Legal parking on the auxiliary lane led to a 24.1% decrease in road capacity. Conversely, prohibiting parking resulted in a 49.99% increase in road segment capacity. Furthermore, the presence of double-parked vehicles, obstructing adjacent lanes, further reduced road capacity by 25.89%. The actual road capacity was observed to be lower than that in the third scenario, as other factors like pedestrian crossings and traffic control methods also contribute to capacity reduction.

Traffic flow characteristics and macroscopic modeling

Speed-flow-density relationship

Speed-flow-density relationship models are valuable for highway design and planning as they offer a quantitative estimate of how speed changes with expected variations in traffic demand (Chiguma 2007).

Establishing the connection between speed, flow, and density can reveal whether on-street parking or other factors affect the actual speed and capacity of a road segment. The methodology used to create the model is outlined below:

- (I) Conducting speed studies in the studied area
- (II) Determination of the passenger car equivalence for each vehicle.
- (III) Examination of the alternative speed-flow-density relationships

Traffic speed

Two approaches are available for conducting speed studies: time-mean speed and space-mean speed. This study opted for the space mean speed method due to its simplicity and ability to derive an average value within the segment. Hence, the speed of random vehicles was assessed at the midpoint of the segment to mitigate interruptions from factors like intersections and pedestrians. To calculate vehicle speed, the travel time over a known distance was recorded from video footage, and this distance was divided by the corresponding time taken to cover it.

Table 8 Passenger car units for different vehicle types

| Vehicle type | PCU value | Sources |
|--------------|-----------|---------------|
| Bicycle | 0.2 | Tamene (2016) |
| Motorcycle | 0.25 | Tamene (2016) |
| Bajaj | 0.4 | Tamene (2016) |
| Small bus | 1 | Tamene (2016) |
| Bus | 2.5 | ERA (2013) |
| Trucks | 2.5 | ERA (2013) |

Passenger car units (PCUs)

For fundamental design considerations, traffic flow is assessed using passenger car units (PCU) concept (Ethiopian Road Authority (ERA) 2013). To accommodate other types of vehicles like bicycles, motorcycles, bajajs, small buses, large buses, and trucks, adjustments are made to the standard PCU values. This adjustment involves aggregating the number of these vehicles using PCU principles. The following table outlines the PCU values for various vehicle types according to the ERA manual and other local sources (Table 8).

Speed-flow and speed-density models

After establishing the PCU values, traffic flow can be expressed in terms of passenger car equivalence.

The data was then examined for consistency across various factors like speed distribution, geometric features, and roadside activities. To assess the consistency in average speed across different sites, ANOVA was applied..

Ho: $\mu_1 = \mu_2 = \mu_3 = \mu_4$ and Ha: $\mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4$.

The analysis results indicated that there was no statistically significant variance in the average speed across the individual sites, as presented in the Table 9.

The study segment exhibited uniformity in terms of geometric features, roadside activities, lane count and width, median type, parking availability, pedestrian presence, and speed limits. Consequently, traffic flow modeling can be conducted at an aggregated level.

Based on the aforementioned plots, there is insufficient evidence to suggest that an alternative model would better fit the field data. Therefore, in the subsequent section, model calibration and comparison of R2 values will be undertaken to identify a model that more accurately represents the field data.

The speed-flow and speed-density relationships are typically described by commonly used models, along with generalized models employed in this study.

Table 9 Comparisons of the average speed at individual sites

| ANOVA | | | | | |
|----------------|----------------|----|-------------|-------|-------|
| Speed | Sum of squares | df | Mean square | F | Sig |
| Between groups | 92.193 | 3 | 30.731 | 2.082 | 0.121 |
| Within groups | 1158.043 | 79 | 14.65877 | | |
| Total | 1250.236 | 82 | 15.24678 | | |

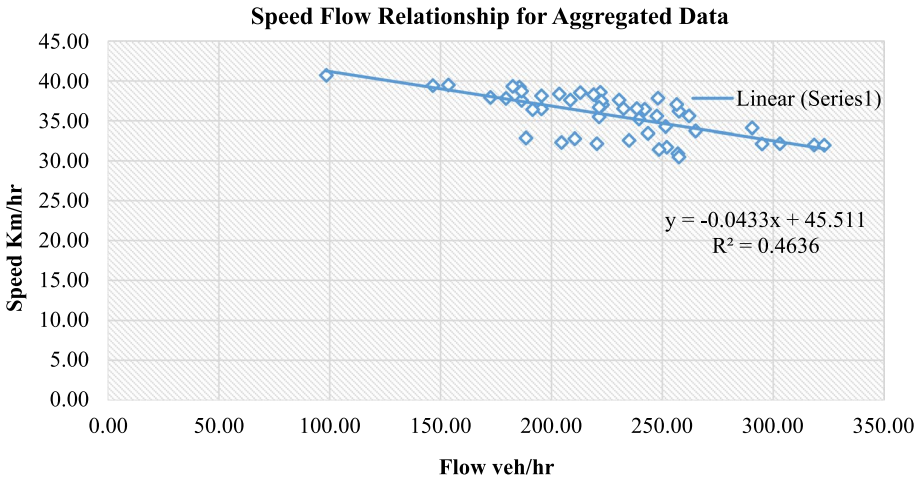


Fig. 7 Flow speed graph for the aggregated data

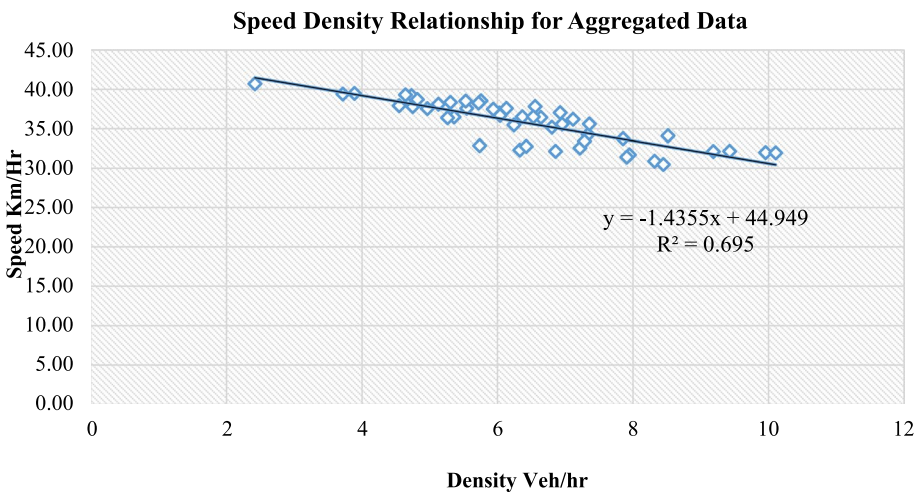


Fig. 8 Speed density graph for the aggregated data

Linear model : Equation : $V = a - b * Q$ (11)

Greenshields model : : Equation : $V = a - b * k$ (12)

or, $Q = K_j * v - k_j * v^2 / v_f$

Greenberg model : Equation : $V = v_o * \ln\left(\frac{k_j}{k}\right)$ (13)

Table 10 Traffic flow models

| Number | Model | Equation | R2 |
|--------|---------------|------------------------------|-------|
| 1 | Linear | $v = 45.511 - 0.0433Q$ | 0.464 |
| 2 | Greenshield's | $V = 44.949 - 1.436K$ | 0.695 |
| 3 | Greenberg's | $V = 51.94 - 8.412 * \ln(k)$ | 0.665 |
| 4 | Underwood's | $V = 46.214 * e^{-0.041k}$ | 0.685 |

Underwood model : Equation : $V = v_f * e^{-k/k_o}$ (14)

where V=average speed, Q= traffic flow, v_f = free flow, K=density, K_j = jam density, K_o =density at maximum flow, V_o = optimum speed, a=free flow speed, and b= slope coefficient

The aggregated speed-flow-density data were used to create overall traffic flow graphs. The following sample graph illustrates the distributions of speed, density, and flow data at an aggregated level (Figs. 7 and 8).

The models calibrated for the individual surveyed sites are depicted in the table below (Table 10):

Model selection The aim of selecting from the general models was to find one that accurately represented the field data from the study sites. It's important to note that only four models were considered in this study due to their simplicity. Selection among these models was based on their goodness-of-fit (R2) values. Both Greenshield's model and Underwood's model demonstrated higher R2 values, but Greenshield's model stood out with a relatively high R2 value of 0.695.

Subsequently, the overall study segment was modeled using the selected Greenshield model.

The calibration result of Greenshield's model is found to be:

$V = 44.949 - 1.436K$, R² values of 0.695.

The road capacity can be calculated using the results of the Greenshield traffic flow model. At maximum flow, the density k_o is half of the jam density, and the speed V_o is half of the free-flow speed. Therefore, the model capacity of the road can be determined as follows:

$$Q_{Max} = \frac{K_j U_f}{4} = \frac{31.301 * 44.949}{4} = 352 \text{ Veh/h}$$

The observed maximum flow rate in the field was 352 vehicles per hour, which was lower than the capacity estimated by the Greenshields model. This indicates that the actual field capacity based on the Greenshields model was 352 vehicles per hour.

Impact analysis of on-street parking

The analysis of the impact of on-street parking on speed and capacity utilized aggregated data from all sites. The assessment of on-street parking's impact on speed involved developing a regression model with and without on-street parking.

Linear regression models incorporate various explanatory variables to describe the variance in the dependent variable. When all potential explanatory variables are included, the model's explanatory power (R2 value) approaches 1. This implies that speed is influenced

Table 11 Regression analysis of on-street parking's impact on traffic flow characteristics

| Variables | (1) Model 1 | (2) Model 2 | (3) Model 3 |
|-------------------|---------------------|---------------------|----------------------|
| Flow (Q) | -0.0413 (-11.14) | -0.0440 (-11.74) | -0.0191 (-1.60) |
| Parking occupancy | | -0.0251 (-2.26) | -0.0301 (-5.10) |
| Density (K) | | | -1.838*** (-5.44) |
| Constant | 46.22 (54.2) | 45.28 (49.39) | 41.3 (40.30) |
| R-squared | 0.7295 | 0.7571 | 0.8547 |
| N | 48 | 48 | 48 |

T statistics in parentheses $p < 0.05$, $p < 0.01$, $p < 0.001$

by numerous factors in the traffic environment, not all of which can be simultaneously studied. In this study, two types of parking were examined: flow and on-street parking.

Initially, a regression model was analyzed that included only flow as an explanatory variable and speed as a dependent variable. The obtained R² value was then compared to the results of another model that included flow, on-street parking, and density as explanatory variables (Table 11).

Case 1 Regression model using flow as an explanatory variable:

$$v = 46.22 - 0.0413Q, \text{ Where } R^2 \text{ is } 0.7295.$$

Case 2 Regression model using flow and parking occupancy as explanatory variables.

$$v = 45.28 - 0.044Q - 0.0251 * \text{par.Occupancy with } R^2 \text{ value of } 0.7571$$

Case 3 Regression model using flow, parking occupancy, and Density as explanatory variables

$$v = 41.3 - 0.0191Q - 0.0301 * \text{par.Occupancy} - 1.838K \text{ with } R^2 \text{ value of } 0.8547$$

The increase in R² value from Case 1 to Case 3 indicates that including parking occupancy as a variable improves the model's ability to explain the variability in speed. The inclusion of parking occupancy as an explanatory variable in the regression model resulted in a negative coefficient for parking occupancy (-0.03), indicating that higher parking occupancy is associated with lower speeds. This suggests that parking occupancy has a measurable effect on vehicle speed, with higher occupancy levels leading to reduced speeds.

A sensitivity analysis

A sensitivity analysis was conducted to assess the significance of traffic flow and parking occupancy on average speed. Both parameters were considered controlling factors, and their impact was evaluated by varying them at a constant rate.

The range for each parameter was chosen based on the potential outcomes. Traffic flow was varied from 50 vehicles per hour to a maximum of 352 vehicles per hour, while parking occupancy was adjusted from 10 to 100% for legal parking.

Table 12 Sensitivity analysis for the current traffic flow of 323veh/h

| Parking occupancy | 0 | 15 | 30 | 45 | 60 | 75 | 90 | 100 |
|-------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Max flow veh/h | 352 | | | | | | | |
| Speed km/h | 40.35 | 38.94 | 37.53 | 37.20 | 36.75 | 36.30 | 35.85 | 35.55 |

The analysis revealed that as traffic flow and parking occupancy increased, average speed decreased. Without parking occupancy, maximum speeds ranged from 40.35 km/h at 50 veh/h to 34.61 km/h at 352 veh/h. With parking occupancy at 100%, the average speed decreased by 4.80 km/h, equivalent to an 8.8% reduction from the original speed. Traffic volume was identified as a significant factor in speed reduction, with parking occupancy also contributing to a 0.05 km/h speed reduction for each increase in parking occupancy (Table 12).

The analysis demonstrates the sensitivity of speed to parking occupancy given the actual traffic flow. Initially, the speed reaches a maximum of 31.1 km/h but decreases to 28.558 km/h due to on-street parking occupancy. This indicates a potential improvement of 4.80 km/h in speed by eliminating on-street parking alone. However, even without on-street parking, the maximum speed remains at 35.55 km/h if no additional measures are implemented. To achieve average vehicle speeds of 40–55 km/h, enhancing road capacity through effective management of traffic activities, including on-street parking, is essential.

Determination of the free-flow speed

The free-flow speed represents the average speed of vehicles on a segment under low-volume conditions, where drivers typically travel at their preferred speeds. To determine this speed for each study site, a sample of vehicles was selected that were considered to be traveling freely. Their speeds were measured by recording the time it took them to cover a set distance using video playback. About 40 vehicle measurements were taken for each site in the morning when traffic was light. The table below summarizes the average speeds recorded for each site (Table 13).

Level of service

The level of service (LOS) on urban streets hinges on the average travel speed of vehicles, which is influenced by the street environment, vehicle interactions, and the traffic control system. On-street parking, falling under the street environment category, affects this speed. Assessing the LOS of an urban street requires data on geometric

Table 13 Summary of field free-flow speeds

| Segment code | Free flow speed km/h | Mean speed km/h | Segment code | Free flow speed km/h | Mean speed km/h |
|--------------|----------------------|-----------------|--------------|----------------------|-----------------|
| 1A | 46.08 | 23.04 | 1B | 43.53 | 21.765 |
| 2A | 44.14 | 22.07 | 2B | 48.02 | 24.01 |
| 3A | 45.59 | 22.795 | 3B | 46 | 23 |
| 4A | 48.37 | 24.185 | 4B | 43.74 | 21.87 |

characteristics, roadside activities, lane number and width, median presence, parking availability, pedestrian presence, and free-flow speed, as outlined in the HCM manual.

In the context of developing countries like Ethiopia, focusing on LOS C instead of LOS D is crucial. LOS C is generally more suitable for urban streets in developing countries, as it is a more realistic target given the infrastructure and operational challenges they face. LOS D, which might be acceptable in more developed urban environments during peak hours, could lead to significant congestion and inefficiencies in developing country contexts. Therefore, prioritizing LOS C can lead to more effective management of traffic flow and on-street parking, helping to reduce congestion and improve overall transportation efficiency in developing country cities.

Ethiopian cities, including Debre Markos Town, often encounter infrastructural and operational challenges that make LOS C a more realistic concern. Factors such as road quality, vehicle conditions, and driver behavior can contribute to congestion even at lower traffic volumes. Focusing on LOS C allows for a better understanding of the challenges in managing traffic flow and on-street parking in a context where infrastructure and transportation systems are still developing. Accordingly, based on the HCM (2010) manual criteria, the street was classified as a class IV urban street, given its high density, significant parking activity, and average free-flow speed ranging from 40 to 55 km/h.

In conclusion, the current traffic flow speed, considering on-street parking occupancy and the free flow speed, placed the study segment between 50 and 67% of free flow speed, classifying it as LOS-C according to the HCM (2010). This classification suggests somewhat restricted ability to maneuver and change lanes in the mid-block, potentially leading to longer queues. With the observed traffic growth in Debre Markos city, there is a rapid increase in traffic demand. Without improvements, the level of service on the streets is expected to decline further.

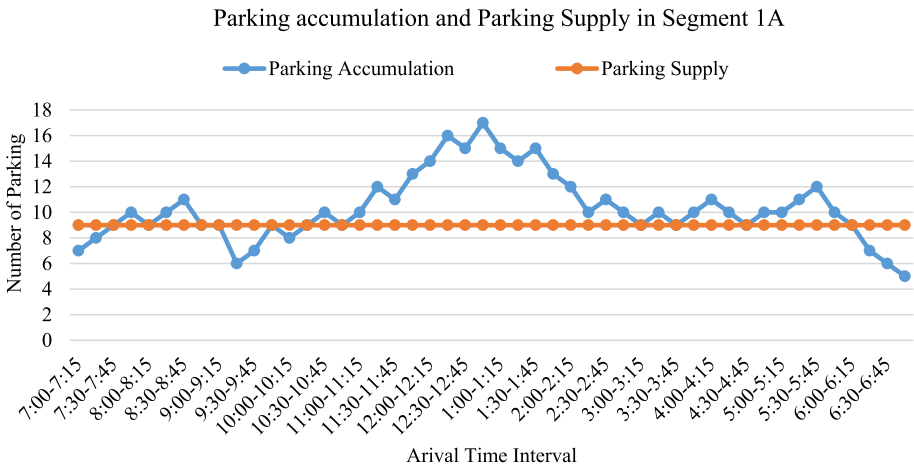


Fig. 9 Parking accumulation vs parking supply in segment 1A

Relationship analysis

Parking supply and demand

This section examines the relationship between the available on-street parking spaces and the parking demand within the study segment to assess the level of pressure on parking availability.

The analysis reveals a significant disparity between the available parking spaces and the actual parking demand. Taking segment 1A as an example, the graph below illustrates the imbalance between parking supply and demand. Despite only having 9 legal parking spaces, the demand consistently exceeds the available supply throughout the study period. This pattern holds true for the entire study segment (Fig. 9).

Given the absence of off-street parking options within the city of Debre Markos, except for limited spaces within certain buildings, all parking demands must be accommodated by roadside parking spaces. Consequently, when the available roadside parking reaches full capacity, drivers resort to illegal parking areas like walkways, crossroads, or double parking lots, as depicted in the preceding figure. Such occurrences were observed to exacerbate traffic congestion and prolong travel times along the section.

The beneficial effects of assigning parking spaces can be discerned by contrasting the summaries of parking demand analysis for both the standard local parking length and the designated 6.1-m parking spaces (Tables 5 and 14). The comparison reveals a notable enhancement in the utilization of street parking facilities. With the designation of parking spaces, the average occupancy level decreased from 104.84 to 71.92%, thereby mitigating the impact of double-parked vehicles and vehicles searching for parking on traffic flow.

Traffic flow and parking demand

Urban parking facilities are fundamental for ensuring smooth urban traffic operations and the sustainable growth of businesses in surrounding areas. Parking has consistently posed challenges in Debre Markos City, particularly within central business districts (CBDs). With the rise in car ownership in the city, the demand for parking is rapidly escalating.

Table 14 Improvement in parking characteristics when 6.1 m marked parking stalls are used

| Site code | Number of space as per standard vehicle length | Parking volume | Parking turnover per day | Parking turnover per hour | Average parking occupancy (%) |
|-----------|--|----------------|--------------------------|---------------------------|-------------------------------|
| 1A | 13 | 243.00 | 18.68 | 1.56 | 81.18 |
| 1B | 12 | 206.00 | 17.81 | 1.48 | 78.37 |
| 2A | 13 | 196.00 | 15.06 | 1.26 | 70.54 |
| 2B | 10 | 160.00 | 15.81 | 1.32 | 80.21 |
| 3A | 12 | 201.00 | 16.47 | 1.37 | 59.75 |
| 3B | 13 | 211.00 | 16.84 | 1.40 | 69.56 |
| 4A | 14 | 189.00 | 13.39 | 1.12 | 62.31 |
| 4B | 12 | 168.00 | 14.04 | 1.17 | 73.40 |
| AV | | | | 1.33 | 71.92 |

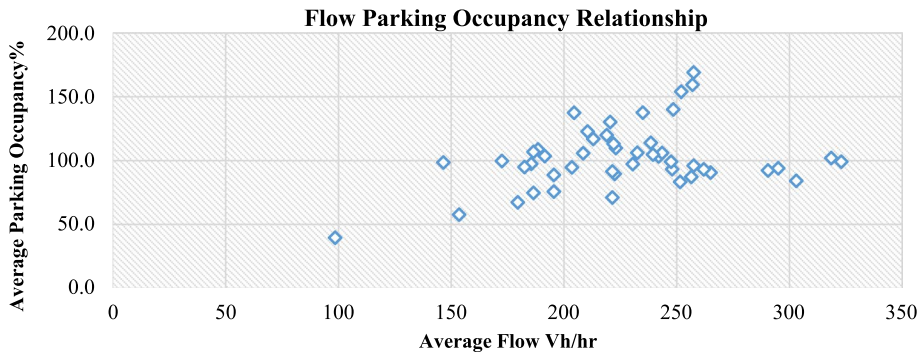


Fig. 10 Relationships between parking occupancy and traffic flow

The study conducted reveals that on-street parking negatively impacts the performance of the studied road segment by increasing interruptions due to maneuvering, escalating illegal parking, and prolonging parking search times. Moreover, parking occupancy was found to be influenced by various factors, including location, time of the day, traffic flow, traffic composition, parking pricing, duration limits, seasonality, parking policies, and enforcement.

The illustrated Fig. 10 above indicates that parking occupancy was notably higher when traffic flow exceeded 180 vehicles per hour. Conversely, with reduced traffic flow, parking occupancy decreased. However, for traffic flows surpassing 250 vehicles per hour, parking occupancy was lower compared to the range of 180–250 vehicles per hour.

Overall, the relationship between traffic flow and parking occupancy is intricate and influenced by various factors, including congestion levels, parking behavior, parking management strategies, and travel patterns. It requires a comprehensive approach to address the challenges identified. The findings of this study underscore the importance of considering all these factors when developing strategies to manage on-street parking and its impact on traffic flow. By addressing congestion levels, improving parking behavior, implementing effective parking management strategies, and understanding travel patterns, it is possible to enhance the overall efficiency of the transportation system in Debre Markos Town, Ethiopia.

Conclusions

Insufficient parking has become a critical transportation issue, especially in central business districts (CBDs) worldwide, leading to congestion in urban transport networks with significant social, economic, and environmental implications. This study aims to fill this knowledge gap by examining the traffic congestion caused by on-street parking and its impacts on traffic flow characteristics on the studied road capacity.

After collecting and analyzing the necessary data, the following conclusions were drawn:

- Due to increased business-related activities, Tuesday and Saturday witnessed the highest vehicle volumes, while Sunday consistently recorded the lowest traffic levels across the entire studied road segment. These findings suggest that traffic patterns are influ-

enced by the days of the week and the level of commercial activities in the area, highlighting the importance of considering such factors in traffic management and planning efforts.

- On Saturdays, parking demand in the study area is mainly influenced by restaurant activity, especially at lunchtime, which occurs during a relatively quiet period for passing traffic. This difference in demand may stem from factors such as the mismatch in peak hours between restaurant activity and passing traffic, the clustering of dining establishments, the parking behavior of restaurant patrons, and the urban layout affecting parking demand patterns. Understanding these factors can aid in improving parking management strategies.
- The parking demand and supply study revealed a significant scarcity of parking stalls in the study segments. The average parking occupancy of the study segment was found to be 104.84%, exceeding the capacity for on-street parking (4.84%). However, if 6.1-m parking stalls are used, the average occupancy would drop to 71.92%.
- The capacity of the road was found to be reduced by 24.1% due to legal parking activities and an additional 25.89% due to illegal double parking activities. Removing on-street parking could improve the capacity by 49.99%.
- Parking occupancy also decreased the average speed of vehicles by 8.8%, with a reduction of 0.05 km/h for each percentage increase in parking occupancy.
- Designating parking stalls based on standard vehicle lengths could increase the number of legal parking spaces by 31.3% and reduce double parking, thereby improving traffic flow speed.

Recommendations

Recommendations based on these findings

Based on the results of my research, which underscore the substantial influence of on-street parking activities on road speed, capacity, and the related economic and social costs in Debre Markos Town, Ethiopia, I suggest the following recommendations:

- *Maintain faded markings for on-street parking spaces* based on field observations, maintaining faded markings for on-street parking spaces can increase availability and reduce interruptions to traffic flow.
- *Utilize unutilized road links for parking* consider utilizing underutilized road links as additional parking spaces in the short term, especially those connected to major segments with lower functionality.
- *Enhance enforcement of parking regulations* given the current lack of regulation and pricing for parking in the researched locality, we recommend strengthening enforcement of parking regulations and implementing effective pricing strategies based on research into parking demand elasticity and economic feasibility.
- *Enforce high-rise buildings to have their own parking spaces* ensure that high-rise buildings, such as shopping malls, are mandated to provide sufficient parking spaces and adhere to proper usage standards.
- *Design roadside parking stalls to increase supply* optimize roadside parking stall designs to maximize available space, reduce maneuvering times, and enhance overall parking supply efficiency.

- *Plan off-street parking locations* proactively plan for off-street parking locations before available spaces are occupied by other land uses. Considerations should prioritize driver convenience, proximity to destinations, walking distances, and other relevant factors.
- *Promote alternative transportation modes* encourage the adoption of alternative transportation modes, such as cycling and walking, to alleviate reliance on private vehicles and reduce the demand for on-street parking.
- *Integrate parking management with urban planning* integrate comprehensive parking management strategies into urban planning initiatives to ensure sustainable and efficient use of urban space.

These recommendations aim to address the challenges posed by on-street parking in Debre Markos Town, Ethiopia, promoting smoother traffic flow, economic efficiency, and improved urban livability.

Future research directions

In Sect. "Future research directions", I outline several recommended studies to further understand and mitigate the impact of on-street parking on traffic flow in urban areas, including the study area of Debre Markos Town, Ethiopia. The estimated costs provided are approximate and based on the specific context of my study area. Here are the detailed future research directions along with their estimated costs:

- *Study the impact of parking demand elasticity on pricing strategies* research the relationship between parking demand elasticity and parking pricing strategies to optimize pricing and improve parking availability. Estimated cost: \$10,000 to \$20,000.
- *Public transportation usage survey* assess the effectiveness of public transportation systems, providing supplementary data on public transport's role in traffic dynamics. Estimated cost: \$8,000–\$10,000.
- *Road condition assessment* evaluate the physical state of the roads to understand the impact of road quality on traffic flow. Estimated cost: \$12,000.
- *Parking demand and supply studies* evaluate the parking demand and supply dynamics in urban areas and identify critical gaps. Estimated cost: \$10,000–\$20,000.
- *Driver and pedestrian behavior studies* assess how driver behavior is influenced by the availability of on-street parking and its impact on traffic safety. Estimated cost: \$10,000 to \$14,000.
- *Simulation and modeling studies* develop and validate traffic simulation models that incorporate on-street parking variables. Estimated cost: \$22,000–\$35,000.
- *Park and ride system studies* assess the effectiveness of park-and-ride systems in alleviating on-street parking-related problems and reducing congestion and parking issues in urban areas. Estimated cost: \$60,000–\$80,000.
- *Policy impact assessment studies* evaluate the effectiveness of different parking management policies and their impact on traffic flow and safety. Estimated cost: \$42,000–\$50,000.

The estimated costs for future studies have been included to provide a clear understanding of the financial requirements for further research and implementation. However, these cost estimates are approximate and specific to the context of Debre Markos

Town, Ethiopia. I recognize that these costs may vary depending on different urban settings and resource availability.

To further support future researchers, the most useful references used in the study include:

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Data availability The authors confirm that the data supporting the findings of this study are available within the article [and/or] its supplementary materials.

Declarations

Conflict of interest I hereby declare that there are no competing interests associated with this manuscript. The research findings, analysis, and conclusions presented in this study are not influenced by any financial, personal, or professional affiliations that could be perceived as having a potential impact on the objectivity and integrity of the research. Including such a statement in the manuscript demonstrates transparency and assures readers that the research is conducted without any conflicts of interest, contributing to the credibility and trustworthiness of the work. I give consent for the manuscript to be published and take responsibility for the correctness of the statements provided in the manuscript.

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