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Capacity Estimation for Four-Lane Inter-Urban Roads in Telangana through Speed Data Analysis

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Abstract

Urban and interstate speed restrictions are mainly enacted to improve road safety, efficiency, and the reduction of travel time and accidents. When evaluating the capacity and free-flow conditions of interurban roads, the 85th percentile of free-flow speed is a regularly used metric. With the use of volume and speed data, this study endeavours to estimate the capacity of four-lane inter-urban highways in Telangana. Moreover, it investigates, taking into account vehicle kinds and speed restrictions, the connection between density, capacity, flow, and speed. Two lengths of inter-urban highways close to Hyderabad were measured for free-flow speeds; these segments included both straight and curving parts of the route. The results show that in Hyderabad, automobiles, lorries, and buses make up the majority of traffic, with two-wheelers coming in second.

Volume and speed capacity analysis becomes essential for understanding the density and flow of different vehicles on specific stretches of the road. Estimating capacity is a fundamental aspect of designing, operating, and planning the "layout of a road network system. The estimation of road capacity, as outlined in the Highway Capacity Manual (HCM) of 2010, relies significantly on the free-flow speed. This speed, indicative of a situation where vehicle movement remains unaffected by the presence of other vehicles in the stretch, holds a pivotal role in capacity assessment. However, the quantification of the influence of free-flow speed on four-lane inter-urban roads is not explicitly addressed in existing methodologies. The heterogeneous nature of traffic on Indian highways, coupled with poor lane discipline, poses challenges for applying simulation techniques. On other hand, values of the Passenger car unit (PCU)" which change homogeneous traffic streams to heterogeneous traffic into a more standardized form. However, PCU values are dynamic and vary under different traffic conditions, necessitating complicated and expensive data collection procedures.

A model is suggested in this study which aims to provide a quick estimation of capacity, removing complexities associated with traditional methodologies, while ensuring accuracy is maintained. This model aims to address the challenges posed by heterogeneous traffic on Indian highways and streamline the estimation process, making it more accessible for field engineers. The model efficiently estimates the capacity of inter-urban roads in Telangana by utilizing speed data and exploring the relationships between flow, speed, density, and capacity.

Keyword: Speed limit, 85th percentile speed, speed compliances, Capacity, Flow, passenger car unit, heterogeneous traffic, operating speed, four-lane roads.

1. Introduction

The posted speed limit plays a crucial role in road safety measures, serving as an indication to drivers of the maximum safe speed permissible on inter-urban roads under ideal conditions such as road geometry, traffic flow, land use patterns, and weather. The main goal of establishing speed limits is to reduce the occurrence and severity of road crashes. Achieving the proper balance is essential because setting the speed limit too low can lead to increased non-compliance rates, while setting it too high may result in more severe injuries. Globally, speeding remains a significant concern, with 'over speeding' contributing to a substantial portion of road accidents, fatalities, and injuries. According to MORTH 2022, 'over speeding' constituted 72.3% of road accidents, 71.2% of total fatalities and 72.8% of total injuries. The data reveals an increase in accidents, fatalities, and injuries associated with 'over speeding' in 2022 compared to the same period in 2021. Analysis of road user categories on National Highways in 2022 indicates that two-wheelers, cars, taxis, vans, and LMVs significantly contribute to accident-related deaths. Understanding the interplay between operating speed, posted speed limits, and road safety is crucial for effective speed management. Traffic rules and regulations are rooted in speed management principles, aiming to strike a balance between travel time, road safety, and overall efficiency.

The 85th percentile speed, indicating the speed at which 85% of vehicles operate under free-flowing conditions, serves as a fundamental benchmark for assessing consistency on a homogeneous stretch of an existing road. In inter-urban settings, several factors contribute to the operating speed, including a wider or paved shoulder, clear road median markings, a higher number of lanes, and a greater volume of cars in the traffic flow. The road design geometry is significantly influenced by drivers' perceptions, with the speed limit in inter-urban areas generally impacted by road curvature, lane count, the presence of medians or on/off-street parking, horizontal curves, and pedestrian infrastructure. Notably, observations suggest that on two-lane roads, traffic tends to comply with the posted speed limit. However, on three- or four-lane roads, there is a tendency for over-speeding, typically exceeding the posted speed limit by 4-5 mph. The interaction of road geometry factors plays a crucial role in shaping the perception of risk and, consequently, the credibility of the speed limit.

In a series of studies, Muhammad et al. (2017) investigated the speeding tendencies of motorcycle riders, discovering that 42.2% exceeded posted speed limits, with over half violating limits on expressways. **Ellen et al. (2018)** explored the benefits of variable speed limit systems, demonstrating their potential to enhance overall traffic safety, particularly when integrated with ramp metering strategies. **Rahim et al. (2018)** evaluated an Automated Enforcement System in Malaysia, finding a significant improvement in speed limit compliance to 96% after the installation of speed detectors and cameras. **Chao Gao et al. (June 2019)** focused on the dispersion of traffic flow speed in Great Britain, emphasizing the need to address compliance issues for safer traffic flow. **Alhomaidat et al. (2021)** assessed the speed spillover effect on freeways, while **Yao et al. (2018)** investigated disparities between perceived safe speed limits and proposed speeds, noting demographic influences on drivers' perceptions. **Martha Leni Siregar's (2021)** assessment of heterogeneous traffic in Indonesia underscored the need for a reassessment of uniform design speeds for inter-urban roads. Additionally, the study by **Ellen F. Grumert and Andreas Tapani** delved into the impact of control algorithm design and system purpose on Variable Speed Limit (VSL) systems, highlighting the significance of specific features for effective implementation, such as a specified application area, early incident detection, short duration, and quick responses to traffic situation changes.

In Michigan, an observed correlation exists between road geometric variables, such as horizontal curves, median width, and shoulder width, and driver speed choices. Wider medians contribute to faster and more uniform traffic flow, creating a sense of comfort and safety for drivers. Results from urban road studies indicate that median presence, bus stop density, curb existence, and adjacent land type significantly influence vehicle speed distribution. Given the crash-prone nature of urban roads, with approximately 60% of accidents occurring on arterial roads, factors like traffic volumes, varied road user speeds, and roadside environments play crucial roles. The credibility of speed limits, aligned with road characteristics and surroundings, is essential for adherence. Roadside features and environmental factors impact driver speed choices, with road type, purpose, land use, and on-street parking affecting speed. Urban roadways experience greater speed reduction than rural roads, with a spillover effect observed near arterial roads, affecting speeds of different vehicle types. Giving due consideration to vulnerable road users, including pedestrians and non-motorized vehicles, is crucial to ensuring the credibility and compliance of speed limits on UK roads.

Accidents are more likely at higher speeds due to longer reaction times and stopping distances, emphasizing the importance of adhering to speed limits for road safety. At a collision speed of 50 km/h, there is an 80% chance of pedestrian fatality, highlighting the need for responsible driving. The use of seatbelts and well-designed vehicles can provide protection for car occupants up to speeds of 70 km/h in front crashes and 50 km/h in most side impacts. The probability of fatal injury for a pedestrian colliding with a vehicle is illustrated in Fig. 1.

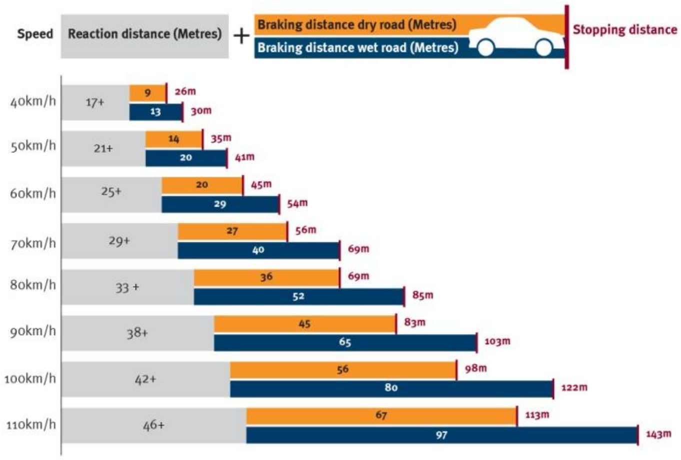

Fig. 1 Illustration of stopping site distance in emergency brake

In Fig. 1, the driver's reaction and braking distances (measured in meters) illustrate the potential consequences of a person suddenly appearing on the road in front of a car. "At a speed of 40 km/h, the distance covered during the driver's reaction time (17 m) exceeds the distance to the person (9 m or 13 m). However, if the vehicle's speed is 30 km/h, it can come to a complete stop before reaching the person". This scenario significantly reduces the likelihood of severe consequences if a person is hit by a car traveling at 40 km/h. It emphasizes that road accidents are more prone to occur at higher speeds, impacting both the driver's reaction time and the distance required for braking.

Several previous studies have explored the impact of weather and environmental factors on speed limits. Analyses have revealed that variables such as time of day, day of the week, season, and weather conditions significantly affect drivers' speed choices, regardless of the posted speed limit. For example, sunny weather tends to lead to more violations of traffic laws compared to rainy seasons. Additionally, observations suggest that non-compliance is more common during late-night hours or early morning, contrasting with midday patterns.

Every year, Saudi Arabia experiences almost 42% of all traffic accidents, a rate more than 4.5 times higher than that of developed nations like the United States. The evident trend indicates a frequent violation of posted speed limits by drivers, particularly on arterial roads where a significant number of motorcycle riders exceed the specified speed limits, necessitating enhanced enforcement measures. Recommendations include employing the Bayesian approach to improve the accuracy of determining the 85th percentile speed, especially when dealing with limited data collection.

Concerning a posted speed limit, a driver's speed choice is influenced by various human factors, including age, gender, education level, driving experience, and opinions about the quality of the road surface. An examination of Indian drivers' speed compliance behavior in evolving driving environments reveals that significant factors affecting speed compliance encompass age, gender, professional qualifications, and driving experience. Notably, compliance is reported to be better in urban driving situations compared to rural driving environments.

2. Study Aim

The precise goals of the current study are set as follows:

- To investigate the impact of speed limits on traffic flow characteristics on an inter-urban road.
- To examine the effects of the posted speed limit on speed-flow characteristics on inter-urban roads.

3. Site Selection and Data Collection

The study locations are National Highways and State Highways roads in India. A reconnaissance survey is conducted to select the location, and the selected stretch must meet the following criteria where roads were selected based on the examined road stretch:

- The road should be straight with uniform geometric features (like number of lanes, median width, and land use pattern).
- There should be no intersections or direct access from nearby land uses.
- Roads susceptible to congestion and high levels of side friction were intentionally avoided, as the objective was to sustain uninterrupted free flow.
- The speed of vehicles was measured both near and far from the posted speed limit signs during low volume conditions.

Based on the above assumptions, an Inter-urban road in Telangana city was selected.

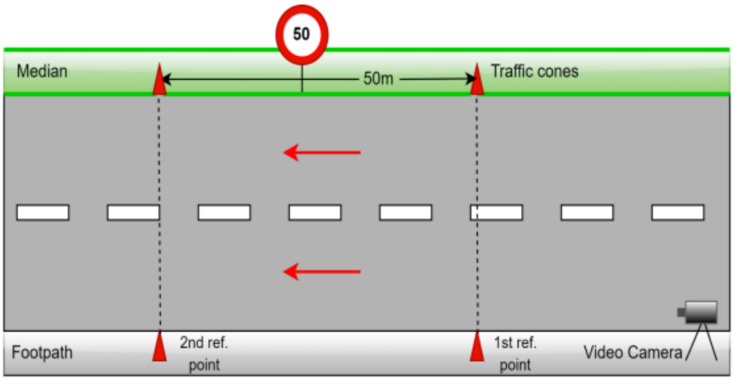

Fig. 2 Outline of mid-block section of road

A mid-block section of base length of 50 m is marked on the road either by placing the traffic cone on either side of the carriageway or by using self-adhesive white tape. The camera is placed on the side of the carriageway, and data were recorded for four hour during the mid hours to capture the free flowing condition. Data like the spot speed, the traffic composition and the category of vehicles, and the specification of road geometry were collected. Based on these, the overview of examine mid-block section of an inter-urban roads were selected Figure 2.
To estimate the mean speed, percentile speeds, geometric features of the road and traffic data have been gathered. Additionally, research has been done to determine the connection between vehicle speed and capacity as well as the safety of the users and vehicles. The selected sites specifications are shown in Table 1.

Table 1 Selected Road Section

Section Code	Section Details	Location of the Road	Carriageway Width (m)	Lane	Speed Limit
A-1	NH-65	**Telangana,** Hydrabad, **(**Vijayavada)	7.0	4 Lane Divided Carriageway	80 kmph
A-2	NH-44	**Telangana,** Hydrabad, **(**Markhal)	7.0	4 Lane Divided Carriageway	60 kmph

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Fig 3 Overview of road in Hyderabad Vijayawada NH-65 (Left) and Markhal NH-44 (Right)

The data extraction involved the use of sports speed measurement software, utilizing video recording to capture images of passing vehicles. Subsequently, an image processing algorithm was applied to calculate the time each vehicle took to traverse the estimated stretch. Information on five-minute volume counts and average stream speeds in a section was derived from these video recordings. Further analysis was carried out using Minitab software, with the goal of determining the speed and flow of vehicles in close proximity to the posted speed limit. The distribution of each vehicle category and the hourly traffic volume at those locations are detailed in Table 2 and Table 3.

Table 2 The distribution of each vehicle category

Vehicle Category	Notation	Length (m)	Width (m)	Rectangular Area (m2)
Small Car	SC	3.72	1.44	5.36
Big car	BC	4.58	1.77	8.11
Two-wheeler	2W	1.87	0.64	1.20
Three-wheeler	3W	3.20	1.40	4.48
Light commercial vehicle	LCV	6.10	2.10	12.81
Medium commercial vehicle	MCV	5.91	2.80	16.54
Heavy commercial vehicles	HCV	15.24	2.44	37.19
Bus	Bus	10.10	2.43	16.28

4. Data extraction and analysis

4.1 Traffic Composition

India experiences high heterogeneous traffic with diverse vehicle types, speeds, and road users. The mix of cars, motorcycles, pedestrians, and other modes creates a dynamic and varied traffic environment, contributing to the complexity of transportation systems in the country. Traffic composition in both cities is shown in fig 3.

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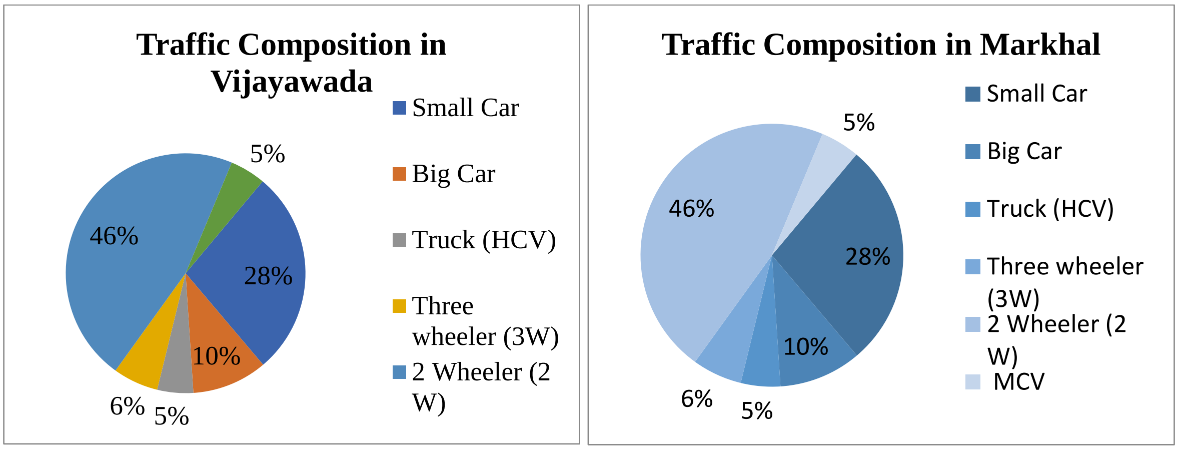

Fig 4 Traffic Composition in Vijayawada and Markhal

In Vijayawada, two-wheelers make up 43% of traffic, followed by small cars (32%), big cars (10%), three-wheelers (10%), and trucks (HCV) (5%). Similarly, in Markhal, two-wheelers constitute 46%, followed by small cars (28%), big cars (10%), three-wheelers (10%), and trucks (HCV) (5%). The prevalent traffic composition indicates the dominance of two-wheelers and small cars on Indian inter-urban roads, with trucks and big cars playing smaller yet noteworthy roles.

Table 3 Traffic volume and composition on sections

Sec.Code	Volume (veh/hr)	Vehicle Categories							
		SC	BC	2w	3W	LCV	MCV	HCV	Bus
A-1	2623	27.41	8.10	42.35	12.97	2.08	-	-	1.87
A-2	842	8.0	6.44	67.88	2.16	5.68	-	-	2.85

In Indian road scenarios, diverse vehicle types coexist without physical separation, resulting in heterogeneous traffic. The transformation of the mixed traffic flow into its homogeneous counterpart is critical for addressing this. We do this by classifying vehicles according to their Passenger Car Unit (PCU) values. Sharing the road with cars of different sizes and types usually leads to less lane discipline. Using Eq.1, we were able to convert the mixed traffic flow into an equal number of Passenger Car Units (PCUs) for each vehicle type in a five-minute count (PCU). Where,

$$PCU = \frac{Vc/Vi}{Ac/Ai} \quad \text{Eq. (1)}$$

PCU - Passenger Car Unit of vehicle category
Vc, Vi - Average speed of vehicle type i, respectively
Ac, Ai - Projected rectangular area of vehicle type i, respectively.

Table 4 PCU Range of Contrastive Vehicles

Sec. Code	Vehicle Categories						
	BC	2W	LCV	HCV	MCV	3W	Bus
T-1	1.23-3.07	0.20-0.28	1.99-2.91	3.03-4.33	-	0.69-1.42	3.68-11.04
T-2	0.91-2.18	0.19-0.37	2.01-4.70	2.86-7.13	-	0.87-2.06	3.61-7.39

The PCU values facilitated the transformation of mixed traffic into a homogeneous flow, aligning with passenger cars. Three speed-density relationships (Green-shields, Underwood, Greenberg) were compared, and the Green-shields model was chosen for capacity estimation due to its early consideration of density's effect on free flow conditions. This model provides a straightforward procedure, and its R2 value aligns with the other models.

Therefore, the capacity for both sections was derived from the curves using the speed-volume method. Figures 6 and 7 illustrate the speed-density and speed-volume curves derived from speed data at section A-1. The solid line represents the curve segment with available field data, while the dotted line in the lower section is extrapolated using assumed density values in density-speed relationships to complete the curve. Capacities for other sections were obtained similarly, as depicted in Figure 5.

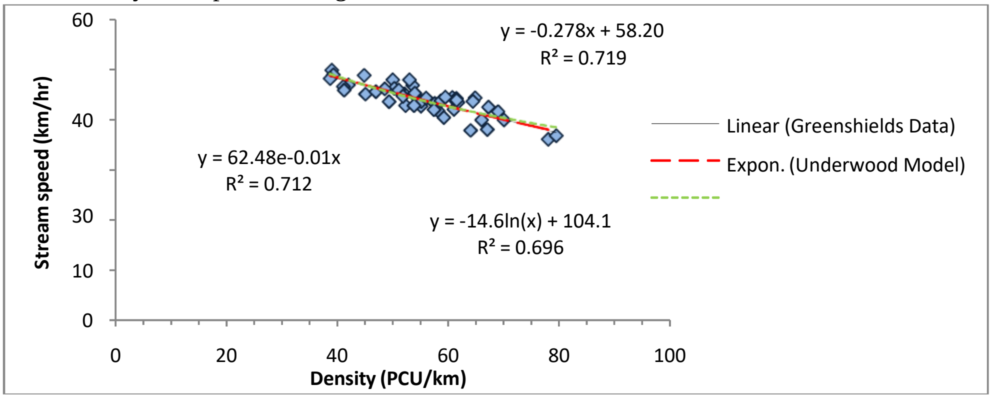

Figure 5 Correlation between speed and density at the specified section A-1

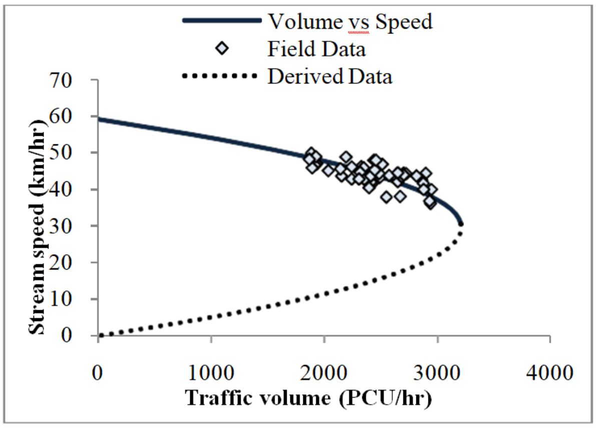

Figure 6 Correlation between speed and volume at the specified section A-1

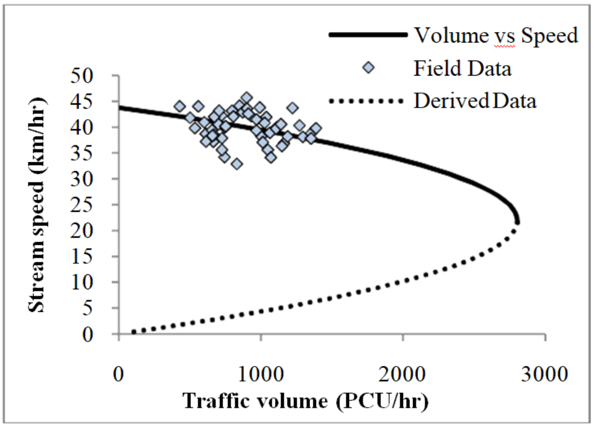

Figure 7 Correlation between speed and volume at the specified section A-2

4.2 Operating speed and Free flow speed

In particular, we are interested in finding out whether there is a relationship between capacity and the 85th percentile free-flow speed, which is the operating speed of passenger vehicles. If the traffic volume is less than

200 PCU/hr, then free-flow conditions are defined by the Highway Capacity Manual (2010) as the absence of obstructions caused by vehicles travelling in either the same or opposite directions as the vehicle going over a given segment. This is described in the handbook as a situation when two moving vehicles have an 8.0 s lead headway or a 5.0 s lag headway. In these cases, the free-flow speed of a passenger vehicle reflects the variables that affect section capacity. Therefore, it is necessary to investigate the connection between capacity and this rate of speed.

To find the 85th percentile speed for each sector, we gathered free-flow speed data for small automobiles and generated cumulative frequency distribution curves with speed frequency. For section A-1, for instance, Figure 12 shows the cumulative frequency distribution and frequency of free-flow speed. Using the same method, Table 5 displays the 85th percentile speeds for both parts.

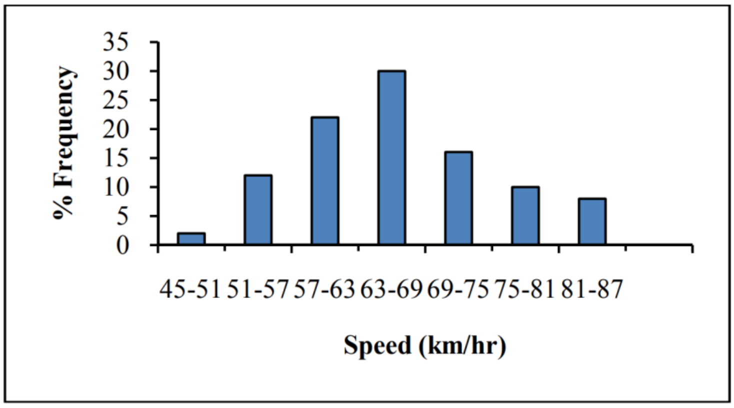

Figure 8 Bar graph depicting the frequency distribution of free-flow speeds at A-1

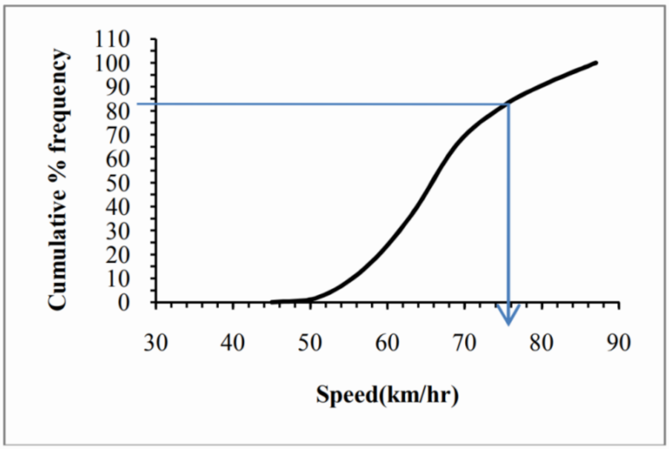

Figure 9 Distribution of speeds in free-flow conditions and the 85th percentile speed can be graphically represented. Of section A-1

Table 5: 85th percentile speeds of both sections

Section. Code	Capacity (PCU/hr)	85^{th} Percentile of Passenger car (km/hr)
A-1	3162	72.91
A-2	2802	68.50

Disparities in traffic mix and driver behaviour across states in India may explain variations in capacity and associated operating speeds across distinct road sections in different locations. Speed limits for passenger automobiles in India are 85 km/hr, whereas the design speeds for national highways are 100 km/hr for flat terrain, as per IRC: 73-1980 and IRC: 52-1981. These speed limitations had no effect on the free-flow speeds that were measured on the study portions.

At each part, we plotted operating speed versus capacity and found the best-fit line. The link between speed and capacity is shown in Figure 6, which shows a second-degree polynomial curve with an R2 value of 0.84. In Equation 2, we can see the link that this study yielded.

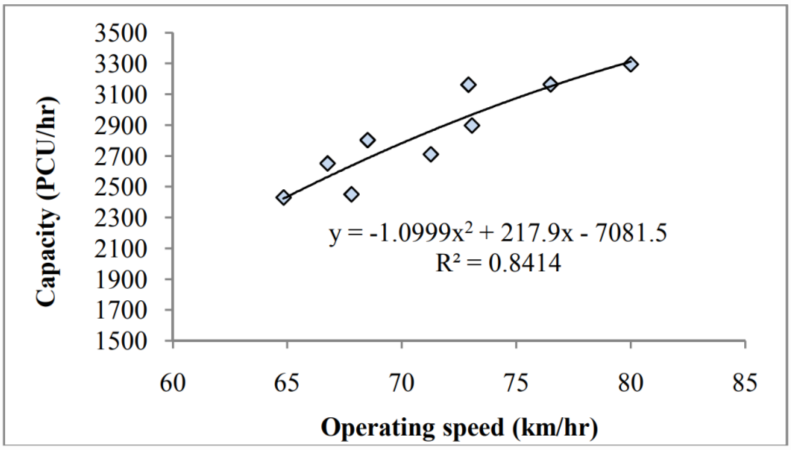

Figure 10 Correlation between operating speed and capacity at two-lane sections.

$C = -1.099v^2 + 217.90v - 7081.5$ Eq. 2

Where;

C = Capacity (PCU/hr)

v = Operating speed (km/hr)

Caution is advised when applying the developed relationship to sections where operating speeds fall outside the range observed in the selected sections.

5. Conclusion

The study aimed to develop a model for estimating the capacity of two-lane two-way inter-urban roads using field data, taking into account geometric features, pavement conditions, and traffic mix. Unlike traditional speed-volume relationship methods that necessitate detailed density levels and Passenger Car Unit (PCU) values for various vehicle types, the proposed model provides a faster yet accurate approach.

The study analyzed the operating speeds of small cars on nine sections of two-lane roads in various parts of India, plotting them against the capacity estimated from field data and speed-volume curves. Results indicated a direct relationship between capacity and operating speed, with a minimum increase of 75 PCU/hr for every 2 km/hr rise in speed.

The proposed model offers a quick and accurate assessment of the capacity of two-lane inter-urban roads, serving as a valuable tool for evaluating facility adequacy and making informed decisions about enhancements. Specifically designed for basic two-lane roads with a 7.0 m width and earthen shoulders on both sides, it simplifies the estimation of the impact of changes in roadway conditions, such as curves or gradients, and allows for easy consideration of the effect of adding paved shoulders.

By significantly reducing data collection costs, the model proves highly beneficial for field engineers in accurately determining section capacity using operating speed data.

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