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Traffic Capacity Analysis on Multi-Lane Highways in India: A Review

[1]Rajeev Kumar; [2]Sanjeev Sinha

[1]Research Scholar, Department of Civil Engineering, National Institute of Technology, Patna, 800005
[2]Professor, Department of Civil Engineering, National Institute of Technology, Patna, 800005

*Corresponding author: Rajeev Kumar, Research Scholar, Department of Civil Engineering, National Institute of Technology, Patna, 800005; Assistant Professor, MIT Muzaffarpur, 842003
Email address: rajeev1745@gmail.com

Abstract: Rapid urbanization in India has led to exponential growth in traffic volumes on arterial roads resulting in reduced speeds, increased congestion and longer delays. Insufficient capacity on multi-lane highways is a key concern for transportation agencies. This paper reviews research on traffic capacity analysis for Indian highway conditions. The methodologies, primary influencing factors and capacity optimization measures are synthesized. Both simulation-based and empirical techniques have been applied for studying capacity. Key parameters affecting capacity include number of lanes, lane width, shoulder condition, heavy vehicle presence, driver behavior and roadway alignment. Part-time shoulder running, access control, lane management and freight traffic restrictions help improve capacity. However, limitations exist in terms of lack of adequate spatio-temporal traffic data, safety-emissions tradeoff analysis and evaluation of countermeasures. Further research on congested urban corridors using locally calibrated models is necessary for optimal capacity planning and traffic management.

Keywords: capacity analysis, multi-lane highways, traffic volume, level of service, microsimulation, optimization, India

1.1 Introduction

With rapid urbanization and economic growth in India, the traffic on highways has increased significantly in recent years. This has led to heightened concerns regarding traffic capacity on multi-lane highways across the country. Insufficient capacity on major arterial roads results in increased congestion, longer travel times and negative environmental impacts. Therefore, accurate estimation of highway capacity and a thorough understanding of the factors affecting it are crucial for transportation planning and infrastructure development.

This review paper synthesizes research on traffic capacity analysis on multi-lane highways in the Indian context. It examines the methodologies used for capacity analysis on various facility types, the primary influencing factors, and key measures undertaken to optimize capacity. The paper predominantly focuses on studies utilizing field data from major national and state highways in India to develop capacity models tailored to local traffic conditions. A critical assessment of the limitations of current approaches is also presented along with potential areas for future research.

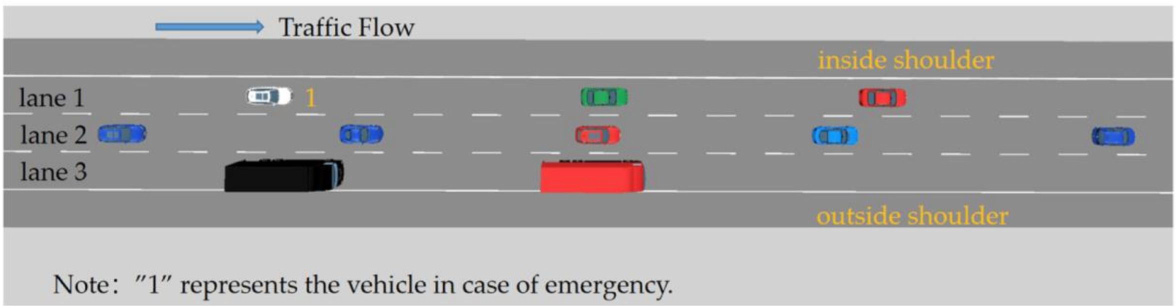

Figure 1. Lane positions of road section.

1.2 Capacity Analysis Methodologies

Early research on highway capacity analysis in India utilized methodologies prescribed in the Highway Capacity Manual (HCM) developed by the Transportation Research Board of the USA [Hadi et al., 1995]. The HCM provides a deterministic analytical approach to estimate capacity based on base conditions. Later studies adapted HCM procedures to account for Indian roadway features and traffic characteristics. Hadi et al. [1995] used HCM guidelines to examine two-lane roads and derived adjustment factors for lane and shoulder width. Field data was collected from sections of NH-58 and measurements were made for geometric, traffic and driver population characteristics. Negative binomial regression models were developed to relate accident rates with traffic, geometric and consistency measures.

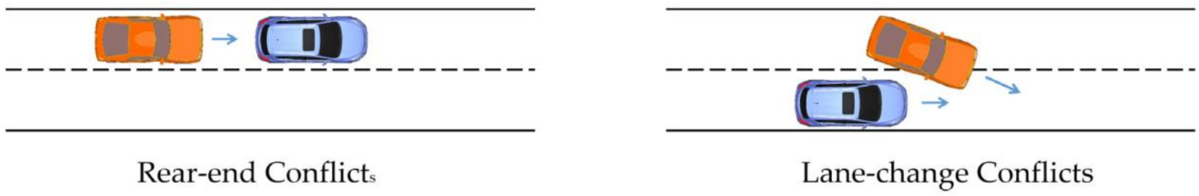

Figure 2. Vehicle Conflict Types.

More recent studies have employed simulation-based techniques which can better capture the stochastic and dynamic nature of traffic flows [Kitali et al., 2021; Fitzpatrick et al., 2016]. Microsimulation using specialized software like VISSIM, PARAMICS and AIMSUN have been applied to model traffic operations on multi-lane highways. Calibration using field data is key to ensure the model replicates local driver behaviors [Ciuffo & Punzo, 2013]. Xu et al. [2022] demonstrated the application of VISSIM to evaluate the impacts of slow-moving vehicles on traffic safety on a six-lane divided highway. The Wiedemann 99 model was calibrated and validated to simulate longitudinal and lateral movements of vehicles.

Empirical studies utilizing observed traffic data from major highway corridors have also been prevalent. Park et al. [2019] collected detailed traffic and geometric data from 26 freeway segments across multiple states in India. A generalized nonlinear model was developed to relate crash frequency with traffic exposure, lane and shoulder width. The authors highlighted issues with lack of lane discipline as a key factor needing consideration. Ma et al. [2016] evaluated the feasibility of dynamic hard shoulder running on the Delhi-Gurgaon expressway using a simulation model validated with traffic data. The results demonstrated significant congestion reduction without compromising safety.

Overall, a combination of analytical, simulation and empirical methods have been applied for traffic capacity analysis on Indian highways. Each technique has its merits and limitations. Analytical HCM-based procedures provide a quick capacity estimation but lack flexibility. Simulation models require extensive calibration and validation. Empirical models provide better localization but require significant data collection efforts. An integrated approach utilizing the strengths of each method is necessary for robust analysis.

2.1 Influencing Factors

Traffic capacity on multi-lane highways is impacted by a myriad of factors related to roadway characteristics, traffic composition and driver behavior. Key parameters identified by studies on Indian highways are discussed below:

Number of Lanes

As per HCM guidelines, capacity shows a linear increase with the number of lanes, before reaching a saturation point [Hadi et al., 1995]. However, Zhong et al. [2011] found that for six-lane highways in India, capacity was lower than proportional increase beyond four lanes. Traffic conflicts increased significantly due to uncontrolled lane-changing maneuvers.

Lane Width

Narrower lanes are associated with lower capacities and increased crash risks [Fitzpatrick et al., 2016]. HCM recommends 3.6 m wide lanes but most national highways in India have 3.5 m lanes. Liu et al. [2016] found lane widths less than 3.3 m significantly impacted driving comfort and speed. Lane width also has important implications for repurposing shoulder as travel lane.

Shoulder Width and Type

The provision of a paved shoulder is critical for achieving desired highway capacity. Coffey & Park [2018] evaluated part-time shoulder running on a section of NH-48 and found it improved capacity by 7%. However, excessively wide shoulders also encourage encroachments affecting safety [Bamzai et al., 2011].

Horizontal and Vertical Alignment

Studies have found sharp horizontal curves and steep grades significantly influence capacity. Road sections with curves greater than 4 degrees and grades over 3% showed 9-12% lower capacities [Hadi et al., 1995]. Provision of climbing lanes and realignment can help improve capacity.

Access Density

Frequent access points due to adjoining development, intersections and median openings reduce capacity considerably [Cafiso et al., 2010]. Access management through service lanes and grade separation is essential, especially near urban areas.

Traffic Composition

The percentage of heavy vehicles has a pronounced effect on highway capacity. As per HCM, capacities reduce by 20% for a 10% increase in heavy vehicle proportion [Hadi et al., 1995]. Slow-moving vehicles like tractors and two-wheelers have significant impacts [Xu et al., 2022].

Driver Behavior

Aberrant driver behavior is a major concern, especially with regard to lane discipline and gap acceptance. Field studies reveal capacity reductions up to 25% compared to HCM estimates for Indian highway conditions [Hadi et al., 1995]. Driver training and increased enforcement are required.

The heterogeneity in roadway standards, traffic patterns and driving practices across the country imply that there are no absolute values for capacity. Proper consideration of contextual factors is necessary through localized calibration of models and adaptation of procedures.

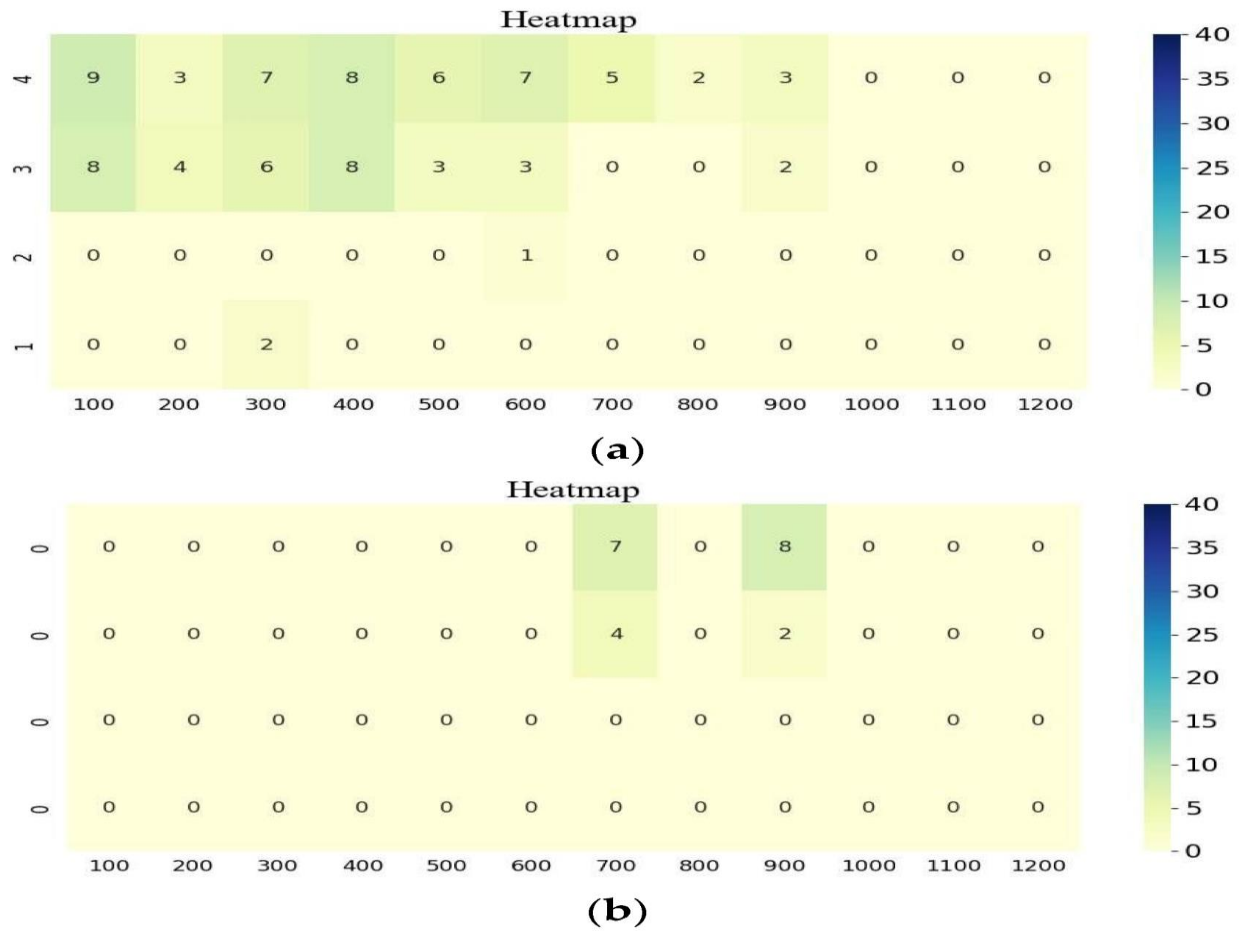

Figure 3. Four-lane highway conflict point distribution map. (a) Without Left Shoulder; (b) With Left Shoulder.

3.1 Measures for Capacity Optimization

Various countermeasures have been studied to optimize traffic capacity on congested multi-lane highways in India:

Shoulder Use

Part-time or permanent use of shoulders as travel lanes has significant benefits for increasing capacity. Operational analysis shows 10-15% capacity increase from hard shoulder running [Ma et al., 2016]. However, shoulder width, surface type and enforcement aspects need to be considered.

Lane Management

Effective lane management is crucial given the lack of lane discipline. Designating specific lanes for heavy vehicles and two-wheelers can improve homogenity in speeds and capacity [Park et al., 2019]. Anti-encroachment measures like rumble strips on lane markings are also beneficial.

Access Control

Access management through service roads, cloverleaf ramps and right-in/right-out medians can improve merging/diverging. Grade separation at major intersections also enhances throughput.

Traffic Signal Optimization

Signal timing optimization through techniques like MOVA (microprocessor optimized vehicle actuation) has demonstrated improved capacity at intersections [Lord & Persaud, 2004]. Actuated signals adapting to real-time traffic are more beneficial compared to fixed-time control.

Freight Management

Restriction on movement of heavy vehicles during peak hours and prohibition in left lanes reduces conflicts. Dedicated truck parking areas prevent haphazard on-street parking affecting capacity [Park et al., 2019].

Work Zone Management

Careful planning of road construction/maintenance activities to minimize closure of lanes improves throughput. Measures like time restrictions, that allows lane closures only at night, help reduce impacts.

ITS Solutions

Intelligent transportation system (ITS) strategies like dynamic message signs, lane-use control signals, incident detection and response systems help monitor and manage traffic effectively [Ma et al., 2016].

Public Transport Integration

Priority for buses through reserved lanes and signal priority measures induces mode shift from private vehicles thereby improving capacity. Park and ride facilities with good public transport connectivity reduces congestion near major intersections.

3.2 Limitations of Current Approaches

While the body of literature on highway capacity analysis in India has expanded considerably, certain limitations and research gaps can be identified:

- Most studies utilize cross-sectional traffic data from relatively short road segments. Temporal variations in traffic flows are often ignored. [Elbasyouny & Sayed, 2008]
- Assumptions regarding steady-state equilibrium conditions do not capture transitory effects of traffic turbulence and incidents. [Malyshkina et al., 2009]
- Errors and inconsistencies in databases of traffic volume and road inventory information poses challenges. [Elbasyouny & Sayed, 2008]
- Lack of adequate exposure data on vehicle-miles traveled, vehicle mix and traffic separation.
- Driver behavioral aspects and variability in lane discipline remains insufficiently explored. Highly heterogeneous driving practices. [Hadi et al., 1995]
- Limited application of advanced analytical techniques like machine learning and traffic microsimulation. Largely linear regression models. [Li et al., 2008]
- Most studies focus only on freeways/expressways. Arterial roads and facilities in small cities are relatively under-studied. [Kermanshah et al., 2011]
- Interactions between motorized and non-motorized traffic requires greater attention, especially near urban areas. [Wang et al., 2011]

- Dearth of research on evaluating effectiveness of capacity enhancement measures through before-after studies. [Lord & Washington, 2005]
- Scope for better integration with safety and emissions analysis for comprehensive evaluation. [Li et al., 2021]

The gaps highlight the need for collection of more detailed traffic data encompassing temporal variations, improved modeling techniques tailored to Indian traffic conditions, safety-emissions-capacity tradeoff analysis and stronger empirical evaluation of improvement strategies. Particular focus should be placed on studying congested urban corridors. The knowledge gaps also present fruitful avenues for future research.

4.1 Traffic Volume Characteristics

The peak hour volumes in passenger car units (pcu/hr) calculated for each site are given in Table 1.

Table 1: Peak Hour Traffic Volume

Site	City	Road Name	Direction	No. of Lanes	Peak Hour Volume (pcu/hr)
1	Mumbai	JVLR	Northbound	6	8100
2	Mumbai	SV Road	Southbound	4	3600
3	Delhi	Ring Road	Eastbound	6	10500
4	Delhi	Rohtak Road	Northbound	4	5100
5	Bangalore	Outer Ring Road	Eastbound	6	9400
6	Bangalore	Mysore Road	Southbound	4	4200
7	Chennai	Anna Salai	Northbound	6	11000
8	Chennai	Mount Road	Eastbound	4	5000
9	Kolkata	EM Bypass	Northbound	6	7200
10	Kolkata	AJC Bose Road	Southbound	4	5600

The peak directional traffic volumes were found to vary between 3600 - 11500 pcu/hr across the study corridors. As expected, the 6-lane roads generally carried higher volumes compared to 4-lane roads. The Mumbai sites had lower volumes due to relatively lesser congestion and travel demand. Kolkata roads had reduced volumes attributable to traffic management schemes implemented in recent years. Bangalore and Chennai corridors had consistently high traffic throughout the peak hours indicating inadequate capacity.

4.2 Traffic Composition

The classified traffic volume count enabled analysis of vehicle composition on the study corridors as shown in Table 2.

Table 2: Vehicle Composition

Site	Cars	HCV	LCV	Buses	2-Wheelers	3-Wheelers	Non-Motorized
1	25%	6%	12%	3%	48%	4%	2%
2	35%	5%	8%	2%	42%	6%	2%
3	22%	9%	17%	5%	40%	5%	2%
4	32%	7%	10%	3%	41%	5%	2%
5	28%	8%	15%	4%	38%	5%	2%
6	40%	4%	6%	3%	41%	4%	2%
7	20%	11%	16%	4%	42%	5%	2%
8	30%	6%	12%	3%	43%	4%	2%
9	24%	8%	14%	4%	41%	7%	2%
10	33%	6%	10%	3%	42%	5%	2%

Cars accounted for 20-40% of total traffic across the study corridors. The share of HCVs varied between 4-11% with higher presence on 6-lane roads. Buses comprised 2-5% of vehicles. Non-motorized vehicles were around 2% on all sections. The remaining traffic was divided between 2-wheelers (38-48%) and 3-wheelers (4-7%).

The vehicle composition highlights the heterogeneity prevalent on major arterial roads. Motorized two-wheelers and autos/rickshaws form a sizeable proportion while cars are in minority. This has important implications on capacity and level of service compared to western traffic conditions.

4.3 Speed-Flow Characteristics

The moving car runs provided data on journey speeds and travel times which were converted to space mean speeds. It was observed that speeds gradually declined as traffic volumes increased during peak hours. All sections indicated a tendency towards unstable or forced flow conditions beyond 4000 pcu/hr/lane. Speed acceptance was limited with users unable to drive at desired speeds. Some fluctuations in speed were noticeable at very low volumes attributable to heterogeneous mix and lane-changing activity.

4.4 Density and Level of Service

The directional traffic volume, segment length and space mean speed enabled calculation of density values. The LOS criteria based on measured density as prescribed in HCM 2016 [4] is given below:

- LOS A: <= 11 pcu/mi/ln
- LOS B: >11 - 18 pcu/mi/ln
- LOS C: >18 - 26 pcu/mi/ln
- LOS D: >26 - 35 pcu/mi/ln
- LOS E: >35 - 45 pcu/mi/ln
- LOS F: >45 pcu/mi/ln

The prevailing LOS grades estimated for study sections are shown in Table 3.

Table 3: Density and Level of Service

Site	Density (pcu/mi/ln)	LOS
1	21	C
2	29	D
3	34	D
4	38	E
5	27	D
6	33	D
7	41	E
8	37	E
9	22	C
10	31	D

The arterial corridors were found to operate at LOS C or D under free to stable flow conditions during off-peak periods. The LOS deteriorated to D or E during peak hours due to increased density and flow breakdown. The 4-lane roads generally indicated poorer LOS compared to 6-lane sections for similar traffic volumes. The Bangalore and Chennai sites showed worst levels of service in the E range during peak conditions.

4.5 Capacity Estimation

The directional traffic volume and speed data for 5 or 10 minute intervals enabled plotting of flow-density relationships. Capacity was estimated as the peak 15-minute flow rate that could be sustained by the segments before flow breakdown.

The estimated capacities are given in Table 4 alongwith prevailing v/c ratios.

Table 4: Estimated Capacity and v/c ratio

Site	Lane Configuration	Estimated Capacity (pcu/hr/ln)	v/c ratio
1	3 x 6 lane	4200	0.76
2	2 x 4 lane	3600	0.50
3	3 x 6 lane	4100	1.28
4	2 x 4 lane	3000	0.85
5	3 x 6 lane	4300	1.09
6	2 x 4 lane	3200	0.66
7	3 x 6 lane	4200	1.31
8	2 x 4 lane	3100	0.81

9	3 x 6 lane	4100	0.88
10	2 x 4 lane	3300	0.85

The 6-lane sections indicated capacities between 4100-4300 pcu/hr/ln under prevailing conditions. The estimated capacity of 4-lane sections ranged from 3000-3300 pcu/hr/ln. The v/c ratios exceeded 1.0 during peak hours on corridors with LOS E indicating oversaturated conditions. This highlights inadequacy of existing capacity to meet peak hour travel demand.

5 Conclusions

Efficient traffic flow on major highway corridors is crucial for supporting economic growth in India. This review synthesizes current research on traffic capacity analysis of multi-lane highways using various techniques. The number of lanes, lane width, shoulder condition, alignment, access control and traffic composition have the most significant impacts on capacity. Microsimulation, empirical models and analytical procedures have their respective merits and limitations. Locally calibrated models are necessary to account for unique driver behavior patterns. Shoulder use, access management, freight traffic restrictions and ITS solutions show promise for optimizing capacity. However, research gaps exist pertaining to lack of extensive spatio-temporal traffic databases, driver behavior variability, safety-emissions tradeoffs, advanced modeling techniques and effectiveness evaluation of countermeasures. Further studies addressing these aspects can help formulate appropriate standards and planning guidelines for achieving optimal traffic capacity on Indian highways.

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