TRANSPORT PROBLEMS 2024 Volume 19 Issue 2
PROBLEMY TRANSPORTU DOI: 10.20858/tp.2023.19.2.04

Keywords: transport infrastructure; capacity utilization; traffic flow; transport supply; transport demand

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TRANSPORT SYSTEM PLANNING: INTERACTION BETWEEN CAPACITY UTILIZATION AND TRAFFIC CONGESTION IN NIGERIA

Summary. One of the greatest challenges most developing countries are facing is the need to improve the transportation systems in their cities. In achieving this, emphasis has been put on the role of infrastructure development to improve the mobility of residents and reduce the negative externalities, such as traffic congestion, associated with most cities in both developed and developing countries. Hence, this study evaluates the impact traffic volume, in relation to available infrastructure capacity, has on traffic congestion, within the dynamics of a rapidly developing urban environment. Though there appears to be a consistent state of slow-moving traffic on two of the roads studied, traffic congestion is not critical, which suggests that available infrastructure is being appropriately utilized. This study found a statistically significant negative relationship between capacity utilization and traffic congestion levels.

1. INTRODUCTION

Transportation, which provides freedom and ease of movement, is a necessary precursor for the social and economic success of any gathering of people in a rural or urban setting [1]. This interaction of transportation with the socio-economic activities of a settlement is represented in the parts that make up the transport system: services, infrastructure, and operations. Studies have shown that even though population does not always have a linear relationship with traffic demand, its influence is an integral part of a comprehensive model of a transport system [2].

A study by Wu, Pei, and Gao [3] showed that traffic demand is made up of the population served by a transport system, the average number of trips, and the proportion of such trips served by available means of transport—rail, bus, taxi, or car—in their formulation of a model to describe the supply-demand ratio in an urban system. Traffic congestion, though, has been a persistent hindrance to the success of such systems since, as traffic density increases, traffic flow decreases [4-5]. This problem was described by Downs [6] as the triple convergence problem—demand will always grow to meet supply. While this categorically negates the idea that additional capacity will solve traffic congestion, the situation can still be managed. Public transport systems, intelligent transport control systems, and socio-cultural policy changes are some of the methods used to alleviate the problem.

While other studies [7] have researched the application of the study of capacity utilization—supply to demand ratio—it remains to be seen how this ratio relates to population (traffic demand) and traffic congestion in a rapidly developing city like Akure. This research attempts to investigate the current relationship between the utilization of available infrastructure capacity and traffic congestion in Akure.

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Thus, this study serves as an indicator for evaluations of future population increase and its impact on traffic congestion levels.

This research poses the following questions:

- What is the relationship between capacity utilization and traffic congestion on the studied roads?
- At what level of capacity utilization does traffic congestion begin on the studied roads?

2. LITERATURE REVIEW

Traffic congestion is defined as the obstruction of vehicular movement resulting from limited road capacity [8]. In more straightforward terms, gridlock ensues when the demand for traffic approaches or exceeds the road network's capacity, as indicated by Vencataya [9, 5]. The field of transportation constitutes a market comprising both transport service providers and the users of these services. The prevailing notion is that a well-functioning transport market should facilitate the alignment of transport supply with transport demand to adequately fulfill mobility requirements. The economic system, characterized by diverse activities across various locations, generates mobility needs that necessitate support from the transport system. The absence of mobility renders infrastructures ineffective, and without infrastructures, mobility cannot occur or would be economically inefficient. This interdependence can be analyzed through two interconnected concepts: transport supply and transport demand. The relationship between transport supply and demand is reciprocal yet asymmetrical.

It is firmly believed that infrastructure investments such as roads, railways, and ports have an important impact on the growth of the country [10-11]. This relationship has been widely used to justify the allocation of funds to the transport sector. The reasons attributed to this include but are not limited to improved accessibility and increased GDP [12]. Often, the overarching aim of policy networks engaged in promoting investment in transport infrastructure is to enhance regional accessibility, which is achieved through decreased travel times or increased travel potential. In the scholarly investigation conducted by Harrison and Todes [13], accessibility was defined as an individual's potential to engage in specific activities at a given location. Park and Goldberg [14] outlined a framework incorporating three interrelated input variables essential for calculating spatial accessibility: supply, demand, and mobility.

Supply, within this context, pertains to the geographical distribution of opportunities or infrastructure that urban residents aspire to access, encompassing employment opportunities and social amenities. On the other hand, *demand* signifies the spatial distribution of city dwellers who are anticipated to capitalize on these opportunities or utilize the existing infrastructure. Consequently, *infrastructure* emerges as a critical determinant contributing to heightened economic activity within a country. Dwiatmoko's research [15] underscores the significance of transportation infrastructure in fostering economic growth, as it enhances competitiveness in the economy. Traffic engineers often draw an analogy between traffic and fluid dynamics, conceptualizing road systems as channels through which a certain volume must flow. However, an alternative perspective posits that urban traffic behaves more like a gas, expanding to occupy the available space [16]. When road enhancements are implemented to lower travel costs, they attract trips from alternative routes, times, and modes of transportation, fostering increased and more frequent travel. This phenomenon, termed "generated traffic" by Hills [17], pertains to the additional vehicle traffic attracted to a specific road. A component of this phenomenon is induced travel, leading to an augmentation of total vehicle miles traveled (VMT). The concept of generated traffic aligns with the economic principle of the "law of demand," which asserts that the consumption of a commodity rises as its price decreases. In this context, improvements to road infrastructure that alleviate congestion, thereby reducing the generalized cost of driving (i.e., travel cost), stimulate greater vehicle use.

In the short term, the appearance of generated traffic is observable as a transition along the demand curve. Reduced congestion makes driving more financially beneficial per mile or kilometer, considering travel time and vehicle running costs. Over time, induced travel indicates an outward shift in the demand curve, contributing to a growing dependence on automobiles within transportation systems and land use patterns. Hence, individuals find themselves increasingly motivated to use cars to sustain a particular level of access to goods, services, and recreational activities [18].

It is important to note that the assertion here is not that expanding road capacity yields no benefits; rather, it underscores that the nature of these benefits is influenced by generated traffic. Road capacity expansion primarily results in increased peak-period mobility, with less pronounced effects on reducing overall traffic congestion. Thus, comprehensive transport planning becomes imperative, necessitating careful project appraisal. In this evaluation, various impacts, including the following, must be considered:

- Generated traffic dampens the predicted congestion alleviation benefits stemming from road capacity expansion, mirroring characteristics of a rebound effect.
- Induced travel imposes costs, including but not limited to downstream congestion, parking costs, traffic accidents, pollution, and other environmental impacts.
- The extra travel that is generated provides relatively modest user benefits since it consists of marginal value trips (those that consumers are most willing to sacrifice).

Litman [19] asserted that these factors must be put into consideration during transport planning and that ignoring these factors may distort planning decisions. Based on the above, the availability of transport infrastructure and effective land use and transportation planning have an impact on traffic flow and capacity utilization, which determine the traffic conditions in an area in the long run.

3. DATA AND METHODS

This study applied methods established by the United States Federal Highway Administration [20] in its Highway Performance Monitoring System to calculate the installed capacity (supply) of selected road transport infrastructure, given the required parameters. The U.S. Highway Performance Monitoring System requires the use of Imperial units; as a result, this study applies a conversion of computational values to metric units.

$$Capacity\ = BaseCapacity\ \times f_{HV}\ \times Lanes \tag{1}$$

where:

BaseCapacity = 1,000 + 20 × FFS: if FFS ≤ 60 (mph)

Otherwise, BaseCapacity = 2,200

FFS is free flow speed, derived by adding 5 to the speed limit, required in miles per hour and equivalent in metric units (60 mph converted to 96.5 km/h).

BaseCapacity = 1,000 + 20 × FFS: if FFS ≤ 96.5 (km/h)

FFS = Free Flow Speed (Speed_Limit + 5)

f_{HV} = adjustment for heavy vehicles

$$f_{HV} = \frac{1}{(1+PT\times(ET-1))} \tag{2}$$

where:

PT = Pct_Peak_Single + Pct_Peak_Combination

ET = Terrain_Type (coded value for the type of terrain)

Lanes = Number of lanes utilized during peak hour

PPS: Percentage peak single-unit trucks and buses (Pct_Peak_Single)

PPS is the value for single-unit truck and bus volumes during peak hours and is represented as a percentage of the total annual average daily traffic (AADT).

% = (Peak hour single-unit trucks and buses/AADT)*100

PPC: Percentage peak combination trucks (Pct_Peak_Combination)

PPC is the value for combination trucks during peak hours and is represented as a percentage of the total annual average daily traffic (AADT).

% = (Peak hour comb. trucks/AADT)*100

The road network and socio-economic activities in the capital city of Ondo State, Akure, feature different road types, conditions, and distinct levels of traffic volume fluctuations that make it a suitable location to carry out this investigation [21].

Oba Adesida Road is a state-managed, three-lane dual carriageway that serves as the major throughway traversing the city's commercial center, Oja Oba. This roadway also connects several residential land-use areas to a mixed commercial-industrial land-use area and shows a significant distribution of vehicles used for passenger transportation (private and commercial alike).

Arakale Road (Road 2), which runs almost parallel to Oba Adesida Road is a three-lane, dual-carriageway traversing a mixed residential-commercial land-use area. Road 2 shows a higher-than-normal distribution of motorcycles, locally referred to as "Okada," used for public transportation. This emphasizes the land use as primarily residential as these motorcycles have become the primary mode of transportation for residents and other road users in the surrounding area.

Road 3, the Ilesha-Akure-Owo Expressway, is a two-lane, single-carriage interstate highway with a notably high distribution of interstate public transport vehicles as well as heavy-duty trucks and trailers. Table 1 shows the modal composition of the roads under study.

Table 1

Modal composition for the roads studied

Vehicle Class	**Road 1**	**Road 2**	**Road 3**
Cars	82.01%	55.16%	63.20%
Motorcycles	14.50%	40.14%	32.69%
Buses	2.18%	2.12%	2.18%
Trucks	1.31%	2.58%	1.92%

Source: Author's fieldwork

Data for this study were collected using automated vehicle counting software deployed to overlook representative intersections and road sections. The lengths of the road sections studied measure about 85 m, 95 m, and 90 m for Roads 1, 2, and 3, respectively. Vehicle classification and counting were achieved by passing video capture from a mounted HD (1280 X 720) camera to open-source computer vision software. Traffic count and vehicle speed data were collected for 21 consecutive days (Monday to Sunday) on three different roads. Traffic count was recorded for two-hour periods at different times of day (morning, afternoon, and evening) to obtain a total of 63 data points.

4. RESULTS

The Nigerian Highway Codes [22] state that the speed limit for motorcycles, private cars, taxis and buses, and trucks on build-up roads (Roads 1 and 2) is 50 km/h. While speed limits differ greatly for different classes of vehicles on highways (Road 3), all classes of vehicles are required to maintain a speed limit of 60 km/h, as the section of the road under study is situated within city limits. With the free flow speed determined by adding 5 to the speed limit, we arrive at values of 55 km/h and 65 km/h for FFS on Roads 1 and 2 and Road 3, respectively. To determine the annual average daily traffic (AADT), the mean value for each day was calculated using the simple averaging method. This served as input to determine the mean daily traffic for the week (Table 2).

This establishes the installed infrastructure capacity of 6192, 6155, and 4507 passenger car equivalents per hour for Road 1, Road 2, and Road 3 respectively. In this study, capacity utilization is concerned with how available transport infrastructure is consumed by traffic demand, hence the use of the term supply-demand ratio [23-24]. Calculated values for capacity utilization are determined by comparing the demand for a given road passenger car unit to the established capacity (supply-demand ratio). For instance, where demand on Road 1 on Day 1 in the morning is 2605, traffic, in effect, utilizes 42.07% of Road 1's infrastructural capacity, 6192. This ratio is described as a percentage to improve readability.

Traffic congestion levels are determined using an inference developed by Hamad and Kikuchi [25] based on the travel speed rate and the very-low-speed rate, which are differentiated into four broad categories: low, moderate, high, and very high. This value is the congestion index, or the percent of time in delay, a representation of the severity of congestion in the observed area or road section.

$$Congestion\ Index = \frac{(Actual\ travel\ time\ for\ the\ section - Free{-}flow\ travel\ time)}{Free{-}flow\ travel\ time} \tag{3}$$

Table 2

Determination of installed capacity (Supply)

	Equation	**Road 1**	**Road 2**	**Road 3**
Speed_Limit (km/h)		50	50	60
Free Flow Speed (km/h)		55	55	65
Annual Average Daily Traffic (AADT)	Mean Annual Traffic	2655	2527	831
Percentage Peak Single-Unit Trucks and Buses (PPS)	(Peak hour Single Unit Trucks & Buses/AADT) * 100	2.18%	2.12%	2.18%
Percentage Peak Combination Trucks (PPC)	(Peak hour Combination Trucks/AADT) * 100	1.31%	2.58%	1.92%
PT	PPS + PPC	3.50%	4.70%	4.11%
ET		1.5	1.5	1.5
Lanes		3	3	2
BaseCapacity	1,000 + 20 × FFS; if FFS ≤ 60 Otherwise, BaseCapacity = 2,200	2100	2100	2300
f_{HV}	$\frac{1}{(1 + PT \times (ET - 1))}$	0.983	0.977	0.980
Lanes		3	3	2
Capacity	$BaseCapacity \times f_{HV} \times Lanes$	**6192**	**6155**	**4507**

Source: Author's fieldwork, [22], …

Travel speed is the rate of speed reduction caused by congestion from the free-flow speed condition:

$$Travel\ speed\ rate = \frac{(Free{-}flow\ speed - Average\ Speed)}{Free{-}flow\ speed} \tag{4}$$

where

Free-flow speed is determined in Table 2 for each road, and average speed is calculated at each recording period by

$$Average\ travel\ speed = \frac{Length\ of\ the\ corridor}{Average\ travel\ time} \tag{5}$$

The very-low-speed rate is computed based on the proportion of time traveling at a very low speed compared with the travel time.

$$Very - low - speed\ rate = \frac{Time\ spent\ in\ delay}{Total\ travel\ time} \tag{6}$$

where Delay is defined as the total travel time at a speed of less than 8 km/h (5 mph).

The values calculated for Travel speed rate and very-low-speed rate individually range between 0 and 1, with 0 being the best condition in which there is no delay or when the average speed is greater than or equal to free-flow speed. Inference and classification for traffic congestion levels are rule-based, with a very low-speed rate assumed to be held constant since recorded vehicle speeds did not fall below 8 km/h (5 mph) [23].

5. DISCUSSION

The data in Table 3 reveal that average vehicle travel speed tended to deteriorate as traffic demand increased to utilize available capacity. This did not always hold true, as average travel speeds remained low even as capacity utilization was of a lower bound. This was demonstrated on Road 1, as only 36.48% of the available capacity was utilized but the average travel speed was 27.07 km/h, with a congestion index of 0.51. In addition, the statistical distribution shows that at some periods with high capacity utilization, traffic conditions remained stable and free-flowing; Road 2 had 53.90% capacity utilization, with a congestion index of 0.45 [23].

Table 3

Statistical summary of collected data per road

	Road 1			**Road 2**			**Road 3**		
Statistics	**Veh. speed (km/h)**	**Cap. Util.**	**Cong. Index**	**Veh. speed (km/h)**	**Cap. Util.**	**Cong. Index**	**Veh. speed (km/h)**	**Cap. Util.**	**Cong. Index**
Min. (Veh. Speed)	26.34	42.07%	0.52	28.23	43.21%	0.49	27.66	24.32%	0.57
Max. (Veh. Speed)	36.81	40.99%	0.38	35.83	29.49%	0.46	31.26	23.43%	0.52
Min. (Cap. Util)	27.45	36.48%	0.50	33.56	21.23%	0.39	30.06	10.29%	0.54
Max. (Cap. Util)	27.45	54.35%	0.50	29.99	53.90%	0.46	30.20	26.22%	0.54
Median	30.09	42.07%	0.45	30.55	42.84%	0.44	30.16	18.88%	0.54
Mean	30.15	42.88%	0.45	31.16	41.05%	0.43	29.72	18.43%	0.54
Max.	36.81	54.35%	0.51	35.83	53.90%	0.49	31.26	26.22%	0.57
Min.	26.34	36.48%	0.44	28.23	53.90%	0.35	27.66	10.29%	0.52

Source: Author's fieldwork

The observed fluctuations in the level of traffic demand on Roads 1 and 2 are consistent with the expected daily peak patterns in the morning and evening due to commuting to and from work [26]. Road 3 exhibited a more even distribution of traffic volume than Roads 1 and 2. That is, the peaks related to the morning and evening commute in the residential land-use areas are less noticeable. This is a result of the continuity of interstate travel irrespective of working hours. In some instances, traffic volume appeared to peak during the afternoon.

In the realm of daily traffic and travel speed fluctuations, this study examined the specific metric of traffic congestion associated with each recorded instance. The degree of congestion was classified into four levels—low, moderate, high, and very high—as outlined by Hamad and Kikuchi [25].

An analysis of the distribution of capacity utilization across all roads and their corresponding congestion levels revealed that traffic experienced smoother flow (traffic congestion index, level B) when capacity utilization remained under 40% and 35% for Roads 1 and 2, respectively. In contrast, there was a marginal deterioration in traffic flow (traffic congestion index, levels C & D) when capacity utilization surpassed 40% and 35% for Roads 1 and 2, respectively.

Interestingly, Road 3 exhibited a consistent level of moderate traffic congestion, with traffic congestion index values ranging between 0.54 and 0.59 across capacity utilization levels varying from 10% to 27%, as depicted in Figure 1. The observed traffic conditions on Road 3 can be attributed to the notable presence of combination trucks on this route. Despite the limited volume of such vehicles on the roadway, their comparatively lower speeds contributed to an apparent state of congestion even before the full capacity was reached.

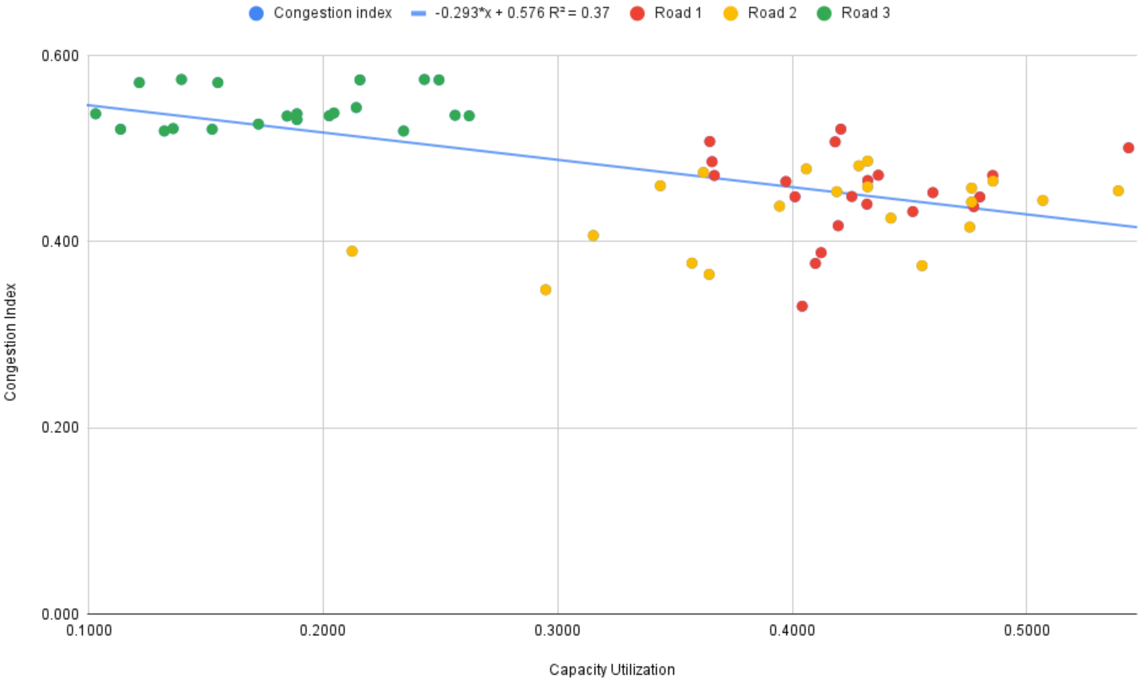

Fig. 1. Trendline plot of capacity utilization in relation to congestion index

Traffic congestion and capacity utilization were moderately negatively correlated, $r(61) = -.608$, $P\text{-value}: <.00001$. This result is significant at $p<0.05$ and indicates the presence of a statistically significant inverse relationship between the investigated variables. This finding does not indicate a relationship to support the assumption that as capacity utilization approaches 100%, traffic flow worsens. The authors note that, on Roads 1 and 2, despite the provision of much roadway furniture and many social amenities, including elevated curbs, carriageway barricades, designated marketplaces, and a pedestrian bridge, very unstable traffic flow is a common occurrence along sections of these roads due to their proximity to the city's major commercial center, thus corroborating the findings of Awoyemi et al. [27]. This is because traders and buyers congregate over goods displayed along the road, thereby inhibiting the flow of traffic for motorists. As such, road users make use of other roads due to the commercial activities on the studied roads that impede vehicular movement.

6. CONCLUSIONS

Urban traffic congestion typically reaches a state of equilibrium, wherein the congestion level becomes discouraging for additional peak-period trips. The augmentation of road capacity facilitates a greater volume of vehicular travel, which predominantly manifests as generated traffic in the short term. The results of our study establish that supply and demand alone, represented by capacity utilization, as indicators are insufficient to model traffic flow conditions. Economic and social activities were influential determinants in this study. Based on the present findings, we expect that the proper maintenance and management of existing infrastructure and traffic conditions, as well as the implementation of policies to abolish street trading, would provide more immediate value than expanding or constructing new transport infrastructure. This would also improve the quality of traffic models by reducing the role of difficult-to-measure factors such as economic and behavioral choices.

Acknowledgments

The authors are grateful to the management of the Federal University of Technology Akure, Nigeria, and the University of Johannesburg, South Africa, for their support in the completion of this research.

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Received 14.12.2022; accepted in revised form 07.06.2024