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THE OPERATIONAL PERFORMANCE OF AL-BAHA'S TWO-LANE MOUNTAINOUS ROADS: A CASE STUDY

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ABSTRACT

The King Fahd two-lane mountainous road serves as a crucial connection between Al-Baha, a key tourist destination, and the coastal towns of Tehama. This study evaluates the road's operational performance by examining its Level of Service (LOS) and capacity, utilizing the procedures from the Highway Capacity Manual (HCM-6th edition, 2016). Data collected during the winter of 2018 was analyzed to determine the road's Average Travel Speed (ATS), Percent Time Spent Following (PTSF), and overall capacity. The analysis revealed that the road operates at a constrained LOS D, with a high PTSF of 77.6%, indicating limited opportunities for overtaking, despite an ATS of 46.2 mph (74.3 kph). The capacity was calculated at 1632 passenger car equivalents per hour, largely influenced by the challenging mountainous terrain and the prevalence of heavy vehicles. These findings underscore the need for road improvements to alleviate congestion, reduce driver frustration, and enhance safety, particularly during peak traffic and tourist seasons.

KEYWORDS: Two-Lane Roads, Road Capacity, Level of Service, Road Performance.

1. INTRODUCTION

The King Fahd two-lane road is a critical artery linking the tourism-rich city of Al-Baha, known for its pleasant summer climate and cool winter, with the coastal towns of Tehama, characterized by hot summer and moderate winter. This road is not only essential for local residents but also plays a significant role in promoting tourism and economic development in the region.

Spanning 30.828 kilometers, the road crosses harsh mountainous terrain, beginning at station 70+000 and ending at station 100+828 on Road 246. The elevation varies significantly, from 575.9 meters to 2,125.9 meters, with a total elevation gain of 1,549.9 meters and an average gradient of 5.03%. This steep climb underscores the road's importance in connecting two regions with starkly different climates. Understanding the operational characteristics of this roadway is vital for ensuring its efficiency and safety, particularly given the varying weather conditions that influence travel patterns.

In transportation engineering, the concepts of level of service (LOS) and capacity are essential for evaluating road performance. Level of service refers to the quality of traffic flow, which is influenced by factors such as speed, travel time, and congestion (TRB, 2016). Capacity, on the other hand, indicates the maximum number of vehicles that can pass through a given section of road in a specific time period (Bhatia & Ghosh 2018).

By assessing these metrics, potential bottlenecks and areas for improvement can be identified, thereby enhancing the overall functionality of the road.

Given the unique geographical and climatic context of this route, it is crucial to analyze how these factors affect traffic flow and road capacity. Seasonal variations, particularly the influx of tourists during the summer months, can lead to significant changes in traffic patterns (Al-Mutairi et al, 2021). This research aims to provide an analysis of the operational characteristics of the King Fahd two-lane mountainous road, utilizing LOS and capacity as primary tools for evaluation. The findings will contribute to better road management strategies, ultimately supporting the growth of tourism and improving the quality of life for residents in both Al-Baha and the Tehama coastal towns.

The operational performance of two-lane mountainous roads is crucial for understanding how terrain and traffic patterns influence the Level of Service (LOS) and capacity, which are fundamental measures for assessing road efficiency and safety. There are various performance measures for evaluating two-lane highways, including those outlined in the Highway Capacity Manual (HCM-6th edition) and alternatives used in different countries. For Class I roads in the HCM, Percent Time Spent Following (PTSF) and Average Travel Speed (ATS) are key measures, while in Germany, density is the primary measure. Countries such as China, Japan, and Denmark are adopting the volume-to-capacity ratio as an evaluation measure for the performance of two- lane roads (Al-Kaisy et al, 2018).

The new version of Highway Capacity Manual, 7th edition, 2022 introduces a new methodology for analyzing two-lane roads. Key updates include the introduction of "Follower Density" as a new service measure, improved speed estimation based on horizontal curvature, and a new approach to estimating free-flow speed using posted speed limits, (Sasahara, 2021).

Two-lane mountainous roads present unique challenges, such as steep grades, sharp curves, and varying weather conditions, which significantly impact traffic flow and safety. As transportation demand increases, especially for tourism and local commerce, comprehensive analysis of these operational characteristics becomes essential for optimizing road performance (Hsu and Hwang, 2019).

Level of Service (LOS) is a qualitative measure describing operational conditions based on factors such as speed, travel time, and traffic density. The HCM provides standardized methodologies for determining LOS, with specific considerations for two-lane roads. Research shows that LOS on mountainous roads is often negatively impacted by steep gradients and frequent curves, leading to slower speeds and increased driver frustration (Wang and Zhao, 2020). As road grades increase, LOS tends to degrade, particularly for heavier vehicles facing steep inclines (Lee and Kim, 2018). **Capacity** refers to the maximum number of vehicles a road can handle under specific conditions and is limited by the design of two-lane mountainous roads. The HCM outlines methods for estimating capacity, considering factors like road geometry and traffic composition. In mountainous areas, capacity is also affected by seasonal traffic peaks, often due to tourism, which can lead to congestion, longer travel times, and safety risks (Smith & Johnson, 2017; Al-Mutairi et al., 2021). Möller and Ahlström, (2020) demonstrate that traffic capacity is often reduced in mountainous areas due to constraints such as narrow lanes and insufficient passing zones. They suggest that incorporating designated passing lanes can significantly improve the effective capacity of these roads, thereby enhancing overall traffic flow.

The relationship between LOS and capacity is key to evaluating mountainous roads. As traffic nears capacity, LOS worsens, increasing travel times and accident risks, especially in areas with challenging geometry (Elvik, 2020). Bham (2022) adds that limited capacity often leads to delays and unsafe driving, particularly during peak tourist times. Vehicle performance is also tied to LOS and capacity. Such findings were supported by Kuo and Shih (2018).

In conclusion, the operational performance of two-lane mountainous roads is heavily influenced by LOS, capacity, and the challenges of road geometry, traffic volume, and vehicle types. Addressing these factors is key to improving efficiency and safety.

2. OBJECTIVES OF THE STUDY

The general objective of this study is to identify the operational conditions of King Fahd's mountainous two-lane highway during ordinary week working days of rush hours. Knowing the operational conditions of the road under study can help the decision-makers take appropriate measures and find solutions to traffic problems before they get worse. The specific operational conditions in this research are capacity and level of service.

3. RESEARCH METHODOLOGY

The methodology for this research is summarized in Figure 1.

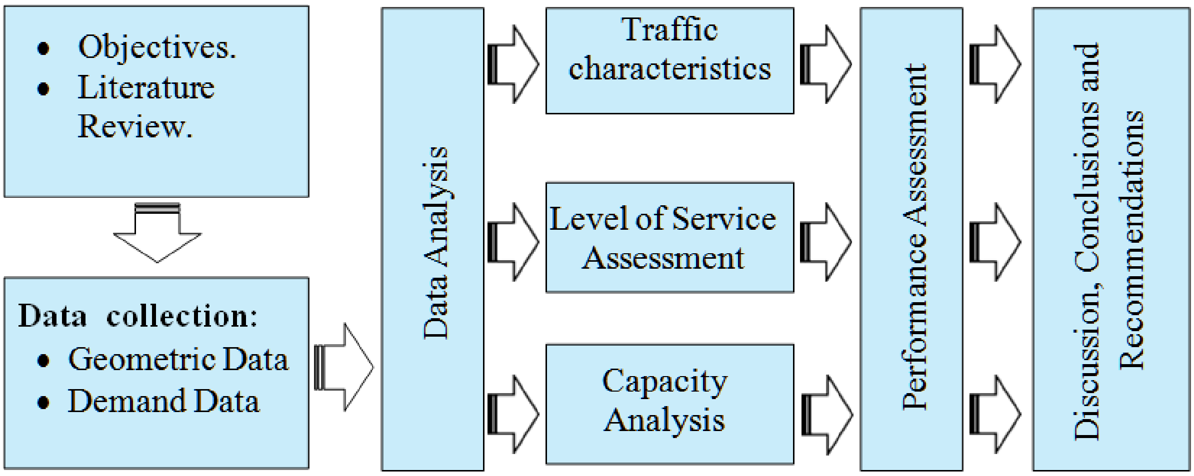

Figure 1: Research Methodology.

4. DATA COLLECTION

Data was collected in winter 2018 covers key aspects for measuring the capacity and level of service of two-lane mountainous roads, including: Detailed hourly traffic volumes, vehicle classification, and speed profiles were recorded. Data was captured during both peak and off-peak periods to provide comprehensive coverage of varying traffic conditions. Geometric data on roadway characteristics, including lane width, shoulder width, roadway grade, and information on horizontal curvature, were systematically gathered to analyze the influence of infrastructure on the operational characteristics of the road. Information on environmental factors, including weather conditions and road surface conditions, was also collected. Some of the data obtained are summarized in Table 1.

5. DATA ANALYSIS

5.1 Traffic Characteristics

The analysis revealed several important operational characteristics of the roadway segment, providing insight into how different factors influence traffic flow. The peak hourly volume (PHV) for the segment was recorded at 779 vehicles per hour (vph), with a distinct variation between the two directions of travel. In the downgrade movement, 544 vehicles were observed, of which 5.5% were heavy vehicles, primarily trucks. In contrast, the upgrade movement accounted for 235 vehicles, with a higher proportion of 7.2% heavy vehicles.

The presence of heavy vehicles is particularly critical in determining the performance of the facility, especially given the 5.4% grade of the road. This incline presents a challenge for larger vehicles, such as trucks, which have reduced climbing abilities and slower speeds on steep grades. As a result, both the speed and the overall traffic flow are significantly affected, especially in the upgrade direction. The slower movement of heavy vehicles on steep sections leads to platooning, where groups of vehicles are forced to travel at reduced speeds, contributing to delays and affecting the overall efficiency of the roadway. Furthermore, the downgrade movement, while having a higher vehicle volume, benefits from gravity, allowing vehicles to maintain the design speed. However, the presence of heavy vehicles still plays a role in influencing traffic behavior, as braking distances and safety considerations become more critical on steep downgrades.

Overall, the heavy vehicle composition, particularly on a roadway with significant grade changes, is a key factor in determining operational performance. Understanding how these vehicles interact with the road geometry and traffic conditions is essential for identifying areas where improvements in capacity or traffic flow management can be made.

5.2 Level of Service (LOS) determination

Although the new version of Highway Capacity Manual, 7th edition, 2022 introduces a new methodology for analyzing two-lane roads. This study used the 6th edition, 2016 procedures to ensure consistency with the data gathered in 2018.

5.2.1 FFS measurement

The Highway Capacity Manual (HCM_2016), 6th Edition provides three methods to estimate Free Flow Speed (FFS) for two-lane highways. The most accurate method is through field measurement. In this study, the field measurement method was adopted. The field Free Flow

Speed FFS was collected during two working days in the early morning time, between 5.30 am and 6.45 am. During this period the traffic flow on the road was under low-demand conditions (the two-way flow rate is less than or equal to 200vph). The FFS was obtained based on 240 vehicles for both directions (144 vehicles in the analysis direction and 96 vehicles for the opposite flow). The average free flow speed of traffic on the analysis direction was found to be 91kph (56.6 mph) with standard deviation of 7.2 kph. While the mean speed for the opposite flow was 72 kph (44.7 mph) with standard deviation of 5.8 kph).

5.2.2 Demand volume adjustment

When estimating both the Average Travel Speed (ATS) and the Percent Time Spent Following (PTSF), the demand volume needs to be adjusted to a flow rate in passenger car per hour under equivalent base conditions. The process for achieving this is presented in this section.

ATS is a key measure of traffic flow quality and user comfort. As traffic volume increases, speeds tend to decrease, particularly on two-lane roads with fewer passing opportunities. If demand volume is not adjusted for ATS, the LOS analysis might not accurately capture the reduction in speed and increased travel time that occurs at higher traffic volumes. By adjusting traffic volume for ATS, the LOS reflects the actual experience of drivers, where slower speeds due to congestion reduce the level of service. The demand volume adjustment formula for ATS are as follows:

$$V_{i,ATS} = \frac{V_i}{PHF * f_{g,ATS} * f_{hv,ATS}} \qquad (1)$$

$$f_{hv,(ATS)} = \frac{1}{1+P_T(E_T-1)+P_R(E_R-1)} \qquad (2)$$

Where: *$V_{i,ATS}$ is the demand flow rate in the i direction for ATS estimation in pc/h, PHF is the peak hour factor, $\mathbf{f_{g,ATS}}$ and $\mathbf{f_{hv,ATS}}$ are the "grade and heavy vehicle" adjustment factors for ATS estimation, respectively. The V_i is the demand volume for direction i in vph. i='d' for analysis direction and 'o' for opposing direction.*

P_T and P_R represent the percentage of trucks and recreational vehicles in the traffic stream respectively. While E_T and E_R represent the passenger car equivalents for trucks and recreational vehicles.

Based on the previous equations, the adjusted demands were calculated for both "analysis and opposite" directions and found to be Vd, ATS = 591pc/h and Vo, ATS 363 pc/h respectively.

Percent Time Spent Following (**PTSF**) represents the proportion of time drivers are forced to follow other vehicles due to limited opportunities for overtaking, a common challenge on two-lane roads. High PTSF values suggest increased congestion and reduced driver comfort. As traffic volumes rise, overtaking becomes more difficult, leading to more drivers being stuck behind slower vehicles. Adjusting demand volume for PTSF helps ensure that the level of service accurately reflects driver frustration and discomfort caused by the inability to pass. The demand volume adjustment formulas for PTSF are the same as those used above in demand adjustment for ATS, with the replacement of ATS by PTSF. Based on those formulas, the adjusted demands for PTSF were calculated for both analysis and opposite directions and found to be $Vd, PTSF$ = 591pc/h and $Vo, PTSF$ 407 pc/h.

5.2.3 ATS and PTSF estimation

Based on the demand adjusted values previously mentioned, the Average Travel Speed in the analysis direction ATSd was calculated using the equation (3). While the PTSFd was estimated according to equations (4) and (5). Given the demand volumes and field conditions, 80% of non- passing zone, ATS was estimated to be 46.2 mph (74.3 kph). While the PTSF was estimated to be 77.6%.

Table 1: Geometric and demand data for road under study.

Geometric Data	
Highway class	I
Lane width	3.8 m
Shoulder width	2 m
Access-point density	0
Terrain	Mountainous
Percent no passing zone	80%
Pavement condition	Good
Demand Data	
Hourly automobile volume (both directions)	779 vph (544, 235)
Length of analysis period	The Peak hour
Peak hour factor	0.90
Directional split	≈ 70/30
Heavy vehicle percentage (both directions)	6.03% trucks (5.5% analysis dir., 7.2% opposite dir.)

$$ATS_d = FFS - 0.00776\,(V_{d,ATS} + V_{o,ATS}) - f_{np,ATS} \quad (3)$$

$$BPTSF_d = 100\left[1 - e^{a(V_d)^b}\right] \quad (4)$$

$$PTSF_d = BPTSF_d + (f_{np,PTSF}) * \left[\frac{V_{d,PTSF}}{V_{d,PTSF} + V_{o,PTSF}}\right] \quad (5)$$

Where:

FFS represent Free Flow Speed, f_{np} is the adjustment factor for (ATS or PTSF) estimation for the non-passing zone in the analysis direction, $V_{d,}$ and V_o represent the demand flow rates for (ATS or PTSF) in the analysis and opposite movements in pc/h.

The $BPTSF_d$ is the Base Time Spent Following in the analysis direction, ***a*** *and* ***b*** *are empirically derived constants based on field data, and to be obtained from HCM tables.*

5.2.4 Finding Level of Service (LOS)

The Level of Service (LOS) for the road segment is determined based on two key measures: Average Travel Speed (ATS) and Percent Time Spent Following (PTSF), as outlined in the Highway Capacity Manual (HCM-2016). The ATS for the segment is calculated at 46.2 mph, corresponding to LOS C, according to Table 2. However, the PTSF, which measures the proportion of time vehicles spend following slower-moving vehicles, is calculated at 77.6%, placing the LOS at D, as shown in the same table. According to the Highway Capacity Manual (HCM-2016) guidelines, the prevailing LOS for two-lane roads is determined by the more conservative (i.e., lower) of the two evaluated measures. In this case, the LOS is determined to be D, based on the higher PTSF. This dual evaluation process highlights the difficulties of assessing LOS on two-lane roads, particularly in mountainous areas like the Al-Baha region. While ATS provides insight into average traffic speeds, the PTSF is a more sensitive indicator of traffic flow quality, especially in regions with limited passing opportunities. ATS reflects the average speed of vehicles on the road, suggesting relatively smooth traffic flow under favorable conditions. An ATS of 46.2 mph corresponds to LOS C, which implies moderate traffic conditions, with drivers able to maintain reasonable speeds given the road's geometric constraints. However, PTSF is a more sensitive indicator of the quality of traffic flow on two-lane roads, especially in mountainous regions where passing opportunities are limited, and steep grades and sharp curves are prevalent. A PTSF of 77.6% indicates that vehicles are spending a significant portion of their travel time following slower-moving vehicles, which greatly reduces their ability to maneuver freely. This condition results in a more frustrating driving experience, as drivers are forced to travel slower than their desired speed due to the lack of passing opportunities, which degrades the LOS to D.

5.3 Capacity Estimation

Capacity estimation is critical in determining the maximum number of vehicles a road can accommodate under current conditions. The capacity is determined by either Equation (6) or

Equation (7), whichever produces the lower estimate. It's important to note that all adjustment factors used in these equations are based on a directional flow rate greater than 900 pc/h as suggested by the HCM-2016.

$$C_{d}\text{-}_{ATS} = 1700\ (f_g * f_{hv})_{ATS} \quad (6)$$

$$C_{d}\text{-}_{PTSF} = 1700\ (f_g * f_{hv})_{PTSF} \quad (7)$$

Where: Cd denotes the capacity in the analysis direction, while ATS, PTSF, f_g, and f_{hv} *are as previously defined.*

The capacity of the road segment was found to be 1700 passenger car equivalents per hour (pc/h) based on the ATS, and slightly lower at 1632 pc/h based on the PTSF. The lower PTSF-based capacity is due to high levels of following behavior and restricted passing opportunities. As a result, the prevailing capacity for the road segment is determined to be 1632 pc/h. This indicates that capacity on two-lane roads, especially in mountainous areas, is more affected by following behavior and the lack of overtaking opportunities rather than just average travel speed.

Table 2: Motorized Vehicle LOS for Two-lane Highways Criteria (HCM-2016).

LOS	***Class I Highways***	
	ATS (mi/h)	***PTSF (%)***
A	> 55	≤35
B	> 50-55	> 35-50
C	> 45-50	> 50-65
D	> 40-45	> 65-80
E	≤40	> 80
F	Demand exceeds capacity	

Note: For Class I highways, LOS is determined by the worst of ATS-based LOS and PTSF-based LOS.

Source: TRB, Highways Capacity Manual- 2016.

6. DISCUSSION OF RESULTS

The analysis of the two-lane highway in the Al-Baha region indicates that it operates under constrained conditions, with the prevailing level of service (LOS) classified as D. This classification reflects significant limitations on mobility, largely due to the lack of passing opportunities and the presence of heavy vehicles on steep or long grades. The PTSF value of 77.6% suggests that drivers frequently experience delays while attempting to overtake slower-moving vehicles, contributing to traffic congestion.

While the ATS of 74.3 kph (46.2 mph) suggests smoother traffic flow and an LOS of C, it does not fully capture the operational challenges posed by heavy vehicles and limited passing zones. The combination of the road grade of 5.4% and a heavy vehicle percentage of 5.5% substantially impacts overall traffic flow, resulting in a constrained driving environment.

The capacity estimate of 1632 pc/h confirms that the road's ability to accommodate traffic is restricted by the mountainous terrain and high PTSF. This indicates that the road is nearing its operational limits, particularly during peak periods. Any future increases in traffic demand, especially from heavy vehicles, could further degrade both the LOS and the road's overall capacity.

7. CONCLUSION

The analysis, using HCM-2016 procedures, reveals that the studied two-lane highway segment operates at LOS D, primarily due to the high percent time spent following and limited passing opportunities. The road's directional capacity is 1632 pc/h, reflecting the constraints imposed by its geometric characteristics and traffic composition.

Improving the road’s LOS would require measures to reduce PTSF, such as increasing the number of passing zones, especially in the first part of the road at the foot of the mountain, such improvement becomes more difficult as approaching the summit of the mountain due to the harsh topography. These improvements could help alleviate driver frustration and improve the overall operational efficiency of this critical transportation link in the Al-Baha region.

8. RECOMMENDATIONS

Based on the study's findings, the following recommendations are proposed:

1. **Enhancement of Passing Zones:** Establish passing zones in the lower sections of the road, where topography is less challenging, to reduce percent time spent following (PTSF) and improve traffic flow.
2. **Seasonal Traffic Variation Studies:** Conduct two studies within the same year to evaluate seasonal **traffic** impacts on road performance—one in winter for Al-Baha residents traveling to the Tehama Plains and another in summer for Tehama residents visiting Al-Baha. Utilize the updated methodologies from the 7th edition of the Highway Capacity Manual (HCM-2022) for accurate results.

3. **Traffic Management Strategies:** Implement traffic management strategies, such as timed vehicle entry **during** peak tourist seasons, to alleviate congestion and maintain level of service (LOS).
4. **Driver Awareness Programs:** Increase awareness of safe driving practices on mountainous roads, focusing on overtaking and frustration management during high PTSF periods.

Adopting these measures can enhance the operational performance of the King Fahd Road, improving its capacity and level of service, thereby supporting regional economic development and tourism growth.

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