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Evaluating the Impact of Pavement Surface Condition on Vehicle Speed and Vehicle Operating Cost: A Case Study of Prithvi and B.P. Highways

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Abstract

Pavement surface condition plays a vital role in traffic flow, road safety, and vehicle operating costs (VOC), particularly on highways in developing countries like Nepal, where road transport is the primary mode of mobility. This research explores the relationship between pavement condition, vehicle speed, and VOC on specific sections of the Prithvi Highway and B.P. Highway. Pavement condition was assessed using the Pavement Condition Index (PCI), derived from detailed visual distress surveys conducted in accordance with ASTM D6433. Eighteen segments—fifteen on the Prithvi Highway and three on the B.P. Highway—were evaluated, with PCI scores ranging from 11 (serious deterioration) to 89 (excellent). Vehicle speeds were recorded via the spot speed method and analyzed based on the 85th percentile speed for three vehicle categories: two-wheelers, light vehicles, and heavy vehicles. The results reveal a strong positive correlation between PCI and operating speed, with significant speed reductions as pavement quality declines. Specifically, the decrease in speed from satisfactory to serious pavement conditions was about 44% for two-wheelers, 56% for light vehicles, and 60% for heavy vehicles. Polynomial regression models most effectively described the PCI–speed relationship, with R^2 values around 0.85–0.86. Vehicle operating costs were estimated using unit VOC rates recommended by JICA. The findings show that poor pavement conditions considerably increase VOC, especially for heavy vehicles, adding up to NPR 26 per km on severely deteriorated pavements. These results highlight the critical need to maintain good pavement conditions to improve traffic flow and reduce user costs, offering guidance for pavement management planning.

Keywords: Pavement Condition Index; Vehicle Speed; Vehicle Operating Cost; Pavement Distress; Correlation

1. Introduction

Pavement condition and traffic operational performance are vital factors that impact the overall efficiency of a road transportation system. Traffic speed, in particular, significantly affects road safety, travel time, congestion, fuel efficiency, and vehicle emissions. Therefore, maintaining road networks at an acceptable service level through regular construction, maintenance, and rehabilitation activities is crucial. The Pavement Condition Index (PCI) is commonly used to monitor and evaluate pavement performance. It is based on observed surface distress and offers an objective evaluation of pavement quality. Developed by the U.S. Army Corps of Engineers, the PCI provides a standardized numerical rating from 0 (failed) to 100 (excellent), assisting transportation agencies in maintenance planning and pavement management decisions (ASTM D6433, 2003). Although the PCI does not directly measure structural capacity, skid resistance, or roughness, it is a valuable tool for identifying maintenance and rehabilitation needs at both the project and network levels. The PCI is also widely used for identifying urgent maintenance and rehabilitation requirements, developing preventive maintenance strategies and budgets, and evaluating pavement materials and designs (Karim et al., 2016). In Nepal, road surface conditions are traditionally assessed using the Surface Distress Index (SDI) and the International Roughness Index (IRI). However, studies have shown that PCI is more reliable and descriptive due to its comprehensive distress classification and rating system. Consequently, PCI has been recommended over SDI and IRI for road condition evaluation in Nepal (Shrestha & Khadka, 2021). Recently, studies based on PCI for pavement condition assessment have increased in Nepal, with several researchers applying PCI to evaluate pavement performance (Kalika et al., 2021; Khadka et al., 2025; Shrestha et al., 2025; Shrestha et al., 2024).

The PCI serves as a more comprehensive indicator of pavement health compared to the IRI because it evaluates both structural integrity and surface quality, rather than focusing solely on longitudinal ride quality. According to Shahin (2005), the ASTM D6433 standard offers a rigorous framework for quantifying the type, severity, and

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density of pavement distress, ensuring a level of standardization that metrics based solely on roughness often lack (Shahin, 1994). Moreover, Arhin et al. (2015) highlight that while IRI is a valuable measure of pavement performance, it does not capture critical surface-level defects such as ravelling or bleeding. These defects are essential for understanding driver safety and tire-pavement interaction (Arhin et al., 2015). In contrast to the SDI, which is often limited to simpler network-level assessments, PCI provides a detailed quantification on a scale from 0 to 100. This granularity allows for the development of more robust statistical regression models when correlating pavement conditions with secondary variables, such as vehicle speed (Piryonesi & El-Diraby, 2020). As a result, the PCI offers the standardized precision necessary for conducting research-grade analyses of how infrastructure deterioration directly impacts individual vehicle operating behaviour.

Several studies have explored the relationship between pavement condition and traffic behaviour, with a particular focus on vehicle speed. Early foundational research by Karan et al. (1978) showed that pavement roughness significantly influences vehicle speed and that ignoring this relationship can lead to substantial errors in economic analyses and road maintenance planning (Karan et al., 1976). Building on this work, subsequent studies confirmed that increased roughness and surface distress generally lead to reductions in free-flow speed and roadway capacity, particularly on two-lane highways (Al-Masaeid et al., 1998; Chandra, 2004). Empirical studies employing roughness indicators have documented a clear decline in average vehicle speed as pavement roughness increases (Yu & Lu, 2014). While some research has reported only marginal improvements in speed following pavement rehabilitation, these findings are often limited by insufficient consideration of vehicle class differences and traffic heterogeneity (Wang et al., 2014). Other studies highlight that pavement condition tends to affect light vehicles more than heavy vehicles due to variations in suspension systems, axle configurations, and manoeuvrability (Hashim et al., 2018). A particularly well-established approach involves correlating the PCI with vehicle operating speed. Numerous studies demonstrate a strong inverse relationship: pavements exhibiting higher distress levels correspond with reduced operating speeds. For instance, Haj-Ismail (1989) found that higher PCI values are associated with increased mean traffic speeds, with no significant difference between day and night conditions (Haj-Ismail, 1989). Regional research further supports these global observations. In Indonesia and other parts of South Asia, studies indicate that severely deteriorated pavements with poor to very poor PCI ratings can experience speed reductions exceeding 50% (Haryati et al., 2023; Setyawan & Kusdiantoro, 2015). Comparable trends have been reported in Pakistan and Nigeria, where progressive declines in PCI values were directly associated with corresponding reductions in free-flow speeds (Ben-Edigbe, 2010; Khan et al., 2023).

Pavement condition directly impacts vehicle operating costs (VOC). According to Volume 7 of the World Bank's Highway Development and Management (HDM-4) model, VOC includes the total costs of road transport, such as fuel, tires, lubricants, spare parts, labour, depreciation, interest, and overheads. Besides vehicle characteristics and technology, VOC is influenced by pavement condition, pavement type, roadway geometry, and operating speed (Robbins & Tran, 2015). Studies in the United States and Asia indicate that deteriorated pavements considerably raise VOC, while smoother pavements result in lower costs and optimal speeds around 60 km/h (Mahendra et al., 2022). In Nepal, JICA has provided VOC estimates for different vehicle types and speeds, highlighting the economic advantages of maintaining good pavement conditions (Japan International Cooperation Agency (JICA), 2017).

This study aims to evaluate how pavement surface condition affects vehicle operating speed and cost along selected sections of the Prithvi Highway and B.P. Highway. The research assesses pavement functional performance using PCI, analyses the relationship between PCI and vehicle speed for different vehicle classes, and estimates the additional vehicle operating costs resulting from poor pavement conditions. The findings offer practical insights into pavement management, maintenance prioritization, and resource allocation in highway infrastructure planning.

2. Methodology

2.1 Study Area and Segment Selection

The Nagdhunga–Mugling section of the Prithvi Highway is a major trade and transit corridor connecting the Kathmandu Valley with the Terai region and India, and it forms part of the Asian Highway network with high traffic (DoR (HMIS-ICT), 2022). Within this corridor, the Dharke–Kurintar section was selected as the primary study area because it has relatively uniform geometric characteristics and minimal gradient variation, allowing clearer observation of the relationship between pavement distress and vehicle speed. However, ongoing upgrades along several sections of the Prithvi Highway limited the availability of pavement segments representing different distress conditions. Therefore, the Bhakundebesi–Mulkot section of the B. P. Highway was included as a supplementary study corridor. This section exhibited vehicle speed characteristics comparable to those observed on the Prithvi Highway and provided the additional pavement distress variability required for analysis of the relationship between pavement condition, vehicle speed, and vehicle operating cost. Road segments were identified prior to the visual distress survey using predefined selection criteria to minimize the influence of confounding factors such as gradient, intersections, roadside activities, and construction zones (Hashim et al., 2023). Based on these criteria, 15 segments were selected along the Naubise–Mugling section of the Prithvi Highway and 3 segments along the Bhakundebesi–Mulkot section of the B. P. Highway, as shown in Figure 1. Fewer segments could be selected along the Bhakundebesi–Mulkot section of the B. P. Highway because other potential sections did not satisfy the study requirements, particularly with respect to geometric uniformity, absence of intersections and roadside disturbances, and the need to avoid sections affected by construction activities.

For the PCI survey, sample units were defined following ASTM D 6433 guidelines, with asphalt concrete (AC) pavement areas of approximately 2,500 sq ft (225 ± 90 m ²). Within each selected segment, one or more representative sample units were established, depending on the availability of homogeneous pavement condition areas. For the spot speed study, segment lengths of 30 m (road width = 6.6 m, resulting in observation area of 198 sqm) on the Prithvi Highway and 45 m (road width = 4.4 m, resulting in observation area of 198 sqm) on the B. P. Highway were adopted to maintain uniform observation areas across both highways, ensuring consistency and comparability in speed measurements between segments despite differences in roadway width. The segmentation approach ensured that each study segment contained clearly defined sample units of known length and area before distress data collection, thereby improving consistency between the PCI survey and speed measurements. All sample units were primarily located along straight roadway sections to capture representative pavement distress conditions while minimizing geometric influences on vehicle speed.

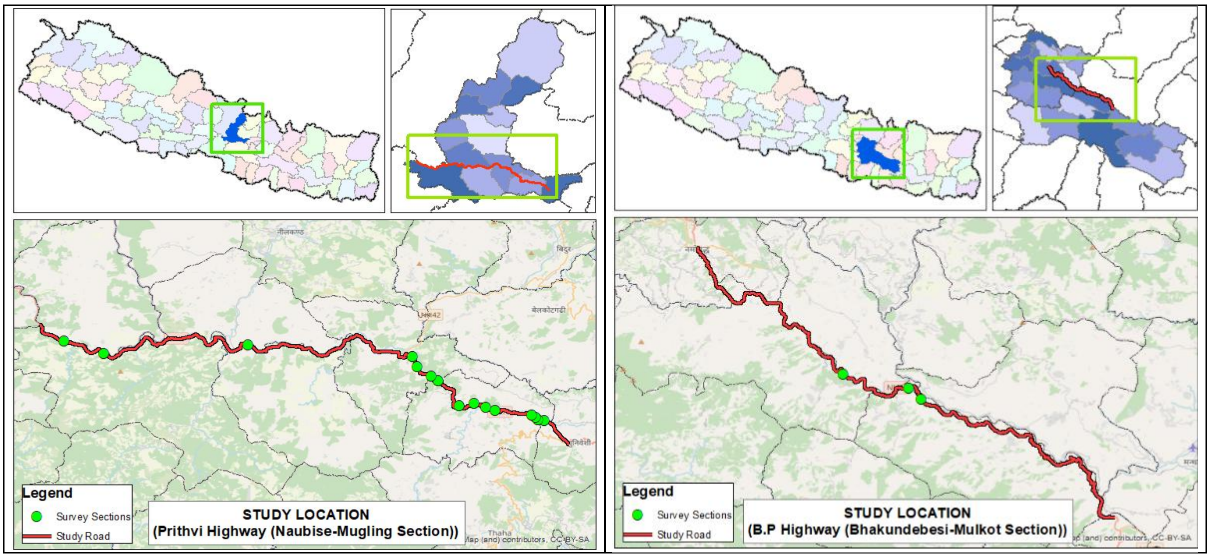


Figure 1 Study Area

2.2 Data Collection

Pavement condition data were collected through visual distress surveys following the guidelines of ASTM D6433 (2003), which provides standardized procedures for assessing flexible pavement performance. The survey involved dividing the study segments into pavement sample units that allowed detailed observation and quantification of surface distress. For asphalt concrete pavements, the sample units were designed to cover areas as mentioned earlier, with adjustments made to accommodate specific field conditions such as irregular lane widths, pavement interruptions, or obstacles that prevented uniform unit dimensions. Within each sample unit, the type, severity, and density of all observed distresses, including potholes, cracking, rutting, and surface defects, were recorded. Severity levels were classified as low, medium, or high based on the depth, width, and extent of the damage, while density was expressed as the percentage of the unit area affected by each distress type (ASTM D6433, 2003).

According to traffic flow theory, operating speed is influenced not only by pavement surface condition but also by traffic volume, traffic density, and traffic composition, particularly the proportion of heavy vehicles. Heavy vehicles contribute significantly to pavement deterioration due to higher axle loads and may also reduce operating speeds due to their lower acceleration and greater space requirements. However, in the present study, spot speed measurements were conducted under cruise conditions, focusing on isolated vehicle movements in which the influence of surrounding vehicles on operating speed was minimal. This approach allowed the recorded speeds to more closely reflect the effect of pavement surface condition rather than interactions within the traffic stream.

Vehicle operating speed was measured using the spot speed method over fixed segment lengths as mentioned earlier. Speed recordings were taken using a stopwatch for 50 samples from each of three vehicle classes: two-wheelers (including motorbikes and scooters), light vehicles (such as cars, jeeps, vans, and pick-ups), and heavy vehicles (comprising minibuses, mini-trucks, buses, and trucks). The 85th percentile speeds were calculated to represent operating speed characteristics. The 85th percentile speed was chosen as the key indicator of operating speed because it reflects driver behaviour in near-free-flow or cruise-condition traffic environments. This measurement is widely utilized in traffic engineering studies to represent operating speed on uninterrupted highway segments (Raccagni et al., 2024; Shirazinejad & Dissanayake, 2020). In this study, spot speed observations were carried out in conditions with minimal influence from surrounding vehicles, allowing for isolated vehicle movement. In such scenarios, the 85th percentile speed offers a reliable estimate of drivers' preferred operating speed in relation to roadway surface characteristics. While space mean speed is frequently used in traffic flow analysis to assess stream performance under varying traffic density, the aim of this study focuses on the impact of pavement surface condition on individual vehicle operating behaviour, rather than on overall traffic stream characteristics. Therefore, using the 85th percentile speed was deemed appropriate for reflecting the influence of pavement conditions on operating speed.

Data on VOC was collected from a study conducted in Kathmandu by JICA in 2023, which detailed the unit values of VOC as per vehicle type and travel speed. The study estimated the values based on the previous study they did in the year 2017. The input data to calculate VOC comprised characteristics of the route and prices of vehicles, tires, fuel and oil, costs of crew members, and maintenance labour (JICA, 2017, 2023).

2.3 Data Analysis

2.3.1 PCI Analysis

The PCI provides a standardized measure of overall pavement condition and allows comparison across different pavement segments. Following visual distress surveys conducted in accordance with ASTM D6433 (2003), PCI values were calculated using a systematic procedure (ASTM D6433, 2003) which is as discussed as follows:

The first step involves determining the degree of damage, or density, which represents the percentage of a sample unit area affected by a specific distress type. Density is calculated as the ratio of the distress area to the total area of the sample unit, expressed as a percentage. Density values are further classified based on the severity of the distress. It is calculated using Equation 1:

$$\text{Density} = \frac{A_d}{A_s} \times 100\% \text{ ....Equation 1}$$

where, A_d is the area affected by a distress type and A_s is the total sample unit area.

Next, the deduct value (DV) for each distress type is determined. Deduct values quantify the reduction in pavement performance caused by a particular distress and are obtained from density-to-deduct value curves provided in ASTM D6433. To account for multiple distress types within a segment, the maximum corrected deduct value (CDV) is calculated. Individual DVs are first arranged in descending order. The allowable number of deductions is calculated using Equation 2. m deduct values are used to iteratively determine the maximum CDV, and total deduct values are corrected using flexible pavement correction curves, taking into account the number of deducts greater than 2.0.

$$m = 1 + \left(\frac{9}{98}\right)(1 - \text{HDV}) \text{ ....Equation 2}$$

where, HDV is the highest individual DV

m = allowable number of deducts, including fractions (must be less than or equal to ten)

Finally, the PCI is calculated by subtracting the maximum corrected deduct value from 100, as presented in Equation 3:

$$\text{PCI} = 100 - \text{CDV}_{max} \text{ ....Equation 3}$$

2.3.2 Correlation Analysis

The relationship between pavement condition and traffic performance was examined by correlating PCI values with the corresponding 85th percentile speeds of different vehicle classes. Statistical models, including linear, exponential, power regressions, and polynomials, were applied to identify the best-fit relationship. The percentage reduction in vehicle speed from good to poor pavement conditions was also analysed. In addition, the correlation between PCI and VOC was assessed using secondary data from JICA. VOC values corresponding to the observed 85th percentile speeds under good and poor pavement conditions were estimated through interpolation. The additional VOC incurred on poor pavements relative to good pavements was subsequently quantified.

Although traffic volume and the percentage of heavy vehicles are known to influence both pavement deterioration and operating speed, detailed, section-wise traffic composition data were not available for all selected study segments during the observation period. Speed measurements were therefore conducted using cruise-condition spot speed observations to minimize traffic interaction effects. Nevertheless, the absence of segment-level traffic composition variables is a limitation of the study and may affect the strength of the observed PCI–speed relationship. Future research incorporating detailed traffic volume and heavy vehicle proportion data would further improve the robustness of the analysis.

3. Results and Discussion

3.1 PCI and Speed

The pavement distress survey revealed that alligator cracking and potholes are the dominant distresses across the study sections, indicating both structural and surface deterioration, presented in Table 1. High-severity potholes were observed in sections PH 01, PH 04, PH 09, and BP 02. Medium- and low-severity potholes were more widespread, suggesting progressive surface degradation. Alligator cracking was the most significant structural distress, appearing at varying severity levels across multiple sections. Section PH 02 exhibited extensive high-severity alligator cracking (50.51%), indicating severe structural failure. High densities of low-severity alligator cracking were also recorded in PH 06, PH 10, PH 14, and PH 15. Other observed distresses included rutting, weathering/ravelling, bumps and sags, lane/shoulder drop-off, polished aggregate, and patching. Notably, BP 01 showed 100% low-severity polished aggregate, indicating adequate structural condition but reduced skid resistance.

Table 1 Distress and its severity

Segment	Distress Type & Severity	Density (%)
PH 01	Potholes (High)	1.48%
PH 01	Potholes (Medium)	0.74%
PH 02	Alligator Cracking (High)	50.51%
PH 02	Potholes (Medium)	2.53%
PH 03	Alligator Cracking (Low)	16.67%
PH 03	Potholes (Low)	0.51%
PH 04	Potholes (High)	1.01%
PH 04	Potholes (Medium)	1.52%
PH 04	Potholes (Low)	3.03%
PH 04	Rutting (Medium)	0.51%
PH 05	Potholes (Medium)	1.01%
PH 05	Potholes (Low)	1.52%
PH 06	Alligator Cracking (Low)	39.90%
PH 06	Weathering/Ravelling (Medium)	0.99%
PH 07	Alligator Cracking (Medium)	9.17%
PH 07	Rutting (Low)	5.56%
PH 08	Alligator Cracking (Low)	7.34%
PH 09	Potholes (High)	1.01%
PH 09	Potholes (Medium)	2.53%
PH 09	Bumps and Sags (Medium)	11.26%
PH 09	Alligator Cracking (Medium)	1.18%
PH 10	Alligator Cracking (Low)	25.64%
PH 11	Alligator Cracking (Medium)	3.19%
PH 11	Lane/Shoulder Drop Off (Low)	15.15%
PH 12	Potholes (Low)	2.53%
PH 12	Alligator Cracking (Low)	8.07%
PH 13	Alligator Cracking (Low)	1.20%
PH 14	Alligator Cracking (Low)	18.56%
PH 15	Alligator Cracking (Low)	20.56%
BP 01	Polished Aggregate (Low)	100.00%
BP 02	Potholes (High)	0.51%
BP 02	Potholes (Low)	3.54%
BP 02	Potholes (Medium)	0.51%
BP 03	Patching (Low)	15.42%

Figure 2 presents the PCI values calculated for individual study sections. The PCI values show considerable variation among the sections, indicating non-uniform pavement performance throughout the corridor. The lowest PCI value of 11 was observed in section PH 09, reflecting a serious pavement condition, whereas the highest PCI value of 89 was recorded in section PH 13, representing an excellent pavement condition beyond the satisfactory range. Most sections exhibit PCI values between 40 and 70, suggesting that a significant portion of the pavement network is in poor to fair condition.

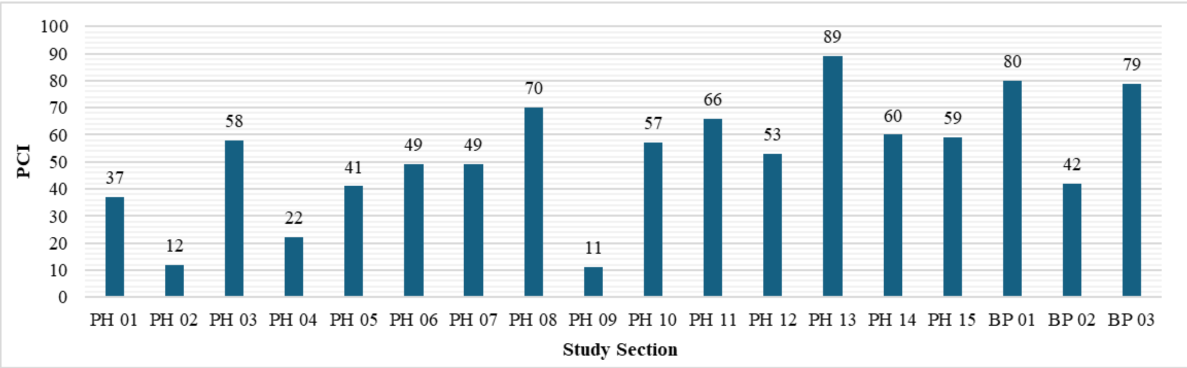
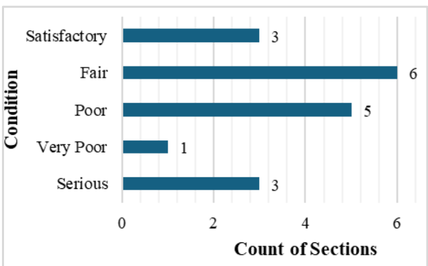


Figure 2 PCI in Study Sections

Figure 3 presents the distribution of pavement condition categories based on PCI classification, namely Serious (10–25), Very Poor (25–40), Poor (40–55), Fair (55–70), and Satisfactory (70–85). Among the study sections, fair conditions dominate the network, with six sections falling into this category. This is followed by five sections classified as Poor. Three sections are categorized as Serious, while the other three sections fall under the Satisfactory category. Only one section is identified as Very Poor, indicating a limited extent of severe deterioration.



	Serious	Very Poor	Poor	Fair	Satisfactory
PH 01	0	1	0	0	0
PH 02	1	0	0	0	0
PH 03	0	0	0	1	0
PH 04	1	0	0	0	0
PH 05	0	0	1	0	0
PH 06	0	0	1	0	0
PH 07	0	0	1	0	0
PH 08	0	0	0	1	0
PH 09	1	0	0	0	0
PH 10	0	0	0	1	0
PH 11	0	0	0	1	0
PH 12	0	0	1	0	0
PH 13	0	0	0	0	1
PH 14	0	0	0	1	0
PH 15	0	0	0	1	0
BP 01	0	0	0	0	1
BP 02	0	0	1	0	0
BP 03	0	0	0	0	1

(a) Count of PCI-based pavement condition observed

(b) Heat map showing PCI-based pavement condition

Figure 3 Pavement Condition in Study Sections

Figure 4 illustrates the spatial distribution of pavement conditions along the study roads. The map clearly demonstrates that pavement condition varies spatially along both corridors, with fair and poor sections dominating the alignment, interspersed with isolated satisfactory segments. Sections classified as serious and very poor are concentrated in specific locations, suggesting the influence of localized factors such as traffic loading, drainage issues, terrain, and maintenance history.

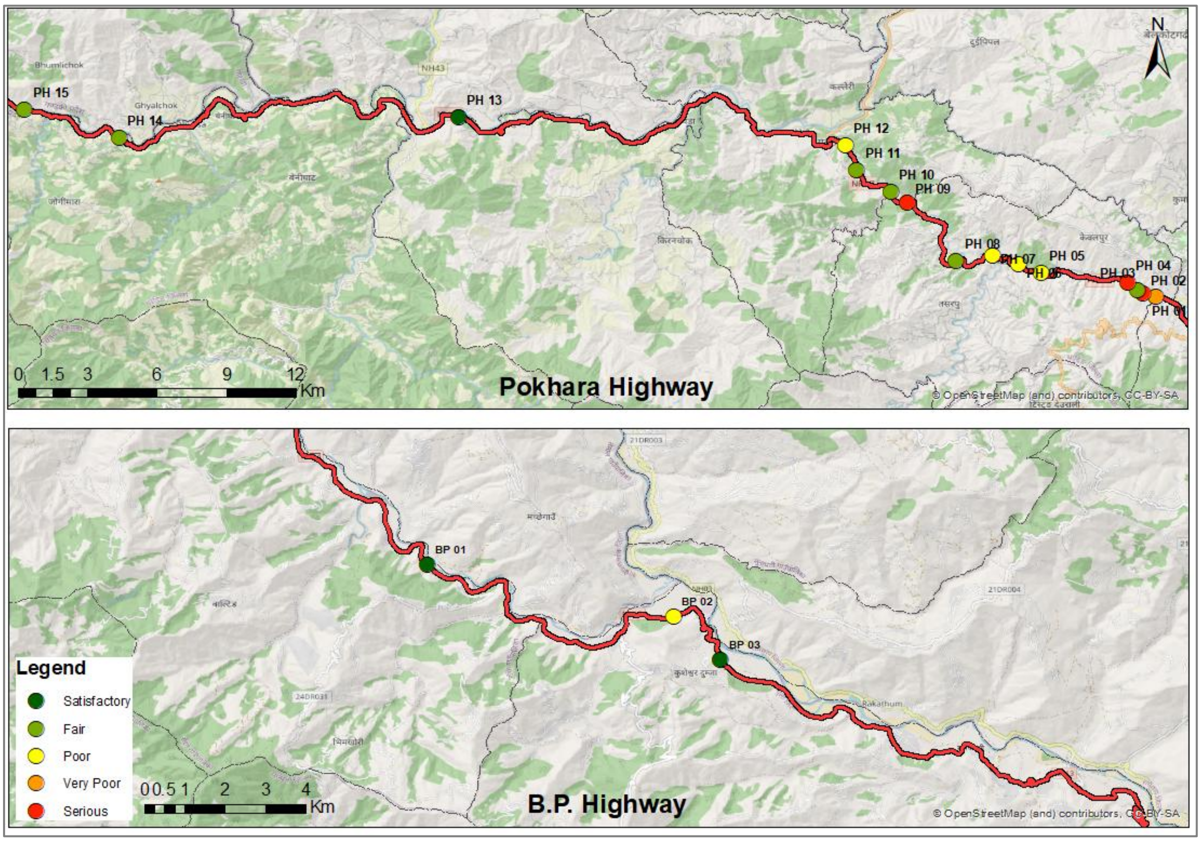


Figure 4 Pavement Condition in Study Sections

Figure 5 illustrates the variation of 85th percentile speeds for two-wheelers, light vehicles, and heavy vehicles across the selected study sections. The results show clear differences in operating speeds among vehicle classes, with two-wheelers consistently recording the highest speeds, followed by light vehicles, while heavy vehicles exhibit the lowest speeds across most sections. This pattern reflects the greater manoeuvrability and acceleration capability of two-wheelers and the higher sensitivity of heavy vehicles to pavement condition and surface irregularities. Considerable variation in operating speed is observed among study sections, indicating the influence of pavement condition and surface distress severity. Sections with comparatively better pavement condition, such as PH 08, PH 13, PH 14, PH 15, BP 01, and BP 03, exhibit higher 85th percentile speeds for all vehicle categories. In contrast, sections such as PH 02, PH 04, PH 09, and BP 02 show noticeably lower speeds, corresponding to poorer pavement conditions and higher distress levels. The most significant speed reduction is observed in PH 09, where all vehicle types operate at substantially lower speeds, suggesting severe surface deterioration.

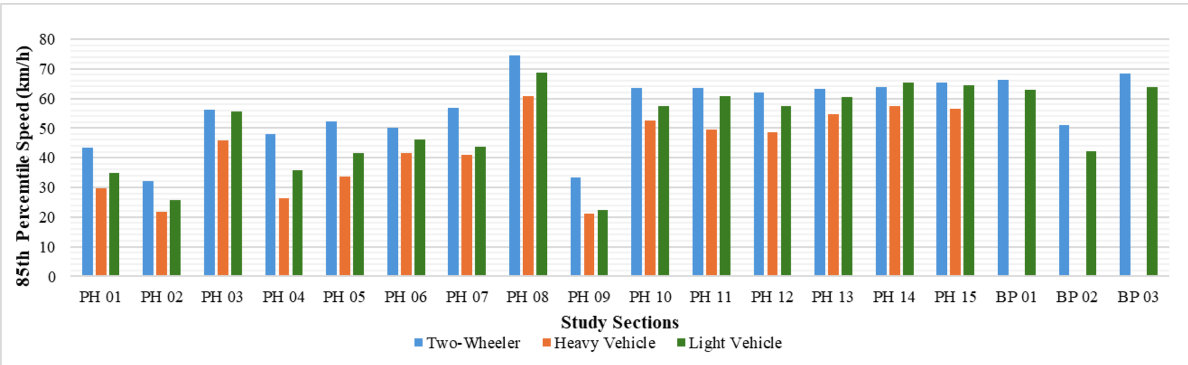
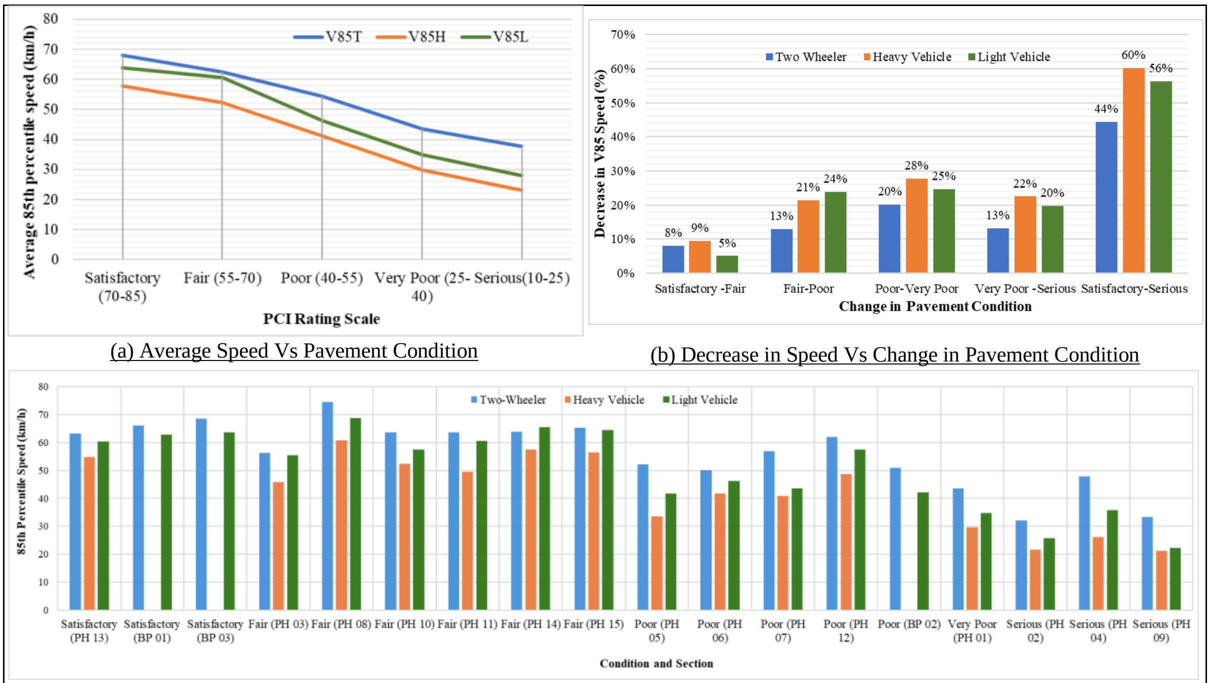


Figure 5 Speed percentiles for different classes of vehicles

3.2 Influence of Pavement Distress on Vehicle Speed

Figure 6 illustrates the relationship between pavement condition and vehicle operating speed expressed in terms of the 85th percentile speed. As shown in Figure 6(a), average speeds for all vehicle categories decrease consistently with the deterioration of pavement condition from satisfactory to serious. Sections rated as satisfactory (PCI 70–85) exhibit the highest speeds, while very poor and serious sections (PCI < 40) show substantial reductions, indicating the strong influence of pavement condition on driving behaviour. Figure 6(b) highlights the percentage decrease in vehicle speed corresponding to changes in pavement condition. The results indicate a progressive reduction in speed as pavement condition worsens, with the most pronounced decrease observed between satisfactory and serious conditions, amounting to approximately 44% for two-wheelers, 60% for heavy vehicles, and 56% for light vehicles. Heavy vehicles experience the greatest speed reduction across all condition transitions, reflecting their higher sensitivity to surface irregularities and structural distress. Figure 6(c) further demonstrates that two-wheelers generally maintain higher speeds compared to light and heavy vehicles under all pavement conditions; however, the rate of speed reduction is evident across all vehicle types as distress severity increases.



(a) Average Speed Vs Pavement Condition

(b) Decrease in Speed Vs Change in Pavement Condition

(c) Speed Vs Condition

Figure 6 Influence of Pavement Distress on Vehicle Speed

3.3 PCI–Speed Correlation and Regression Analysis

Figure 7 presents the relationship between the 85th percentile speed (V85) and Pavement Condition Index (PCI) using linear, exponential, power, and polynomial regression models for two-wheelers, light vehicles, and heavy vehicles. All regression forms indicate a strong positive relationship between PCI and vehicle speed, confirming that vehicle operating speed increases as pavement condition improves. Heavy vehicles consistently show slightly lower speed values for a given PCI, reflecting their greater sensitivity to pavement irregularities. Polynomial regression yields the highest R^2 values (≈0.85–0.86) for all vehicle types, followed closely by the power model. Linear regression provides a reasonable fit, whereas the exponential model shows comparatively lower explanatory power. These results indicate that non-linear models better capture the speed–PCI relationship, especially under deteriorated pavement conditions.

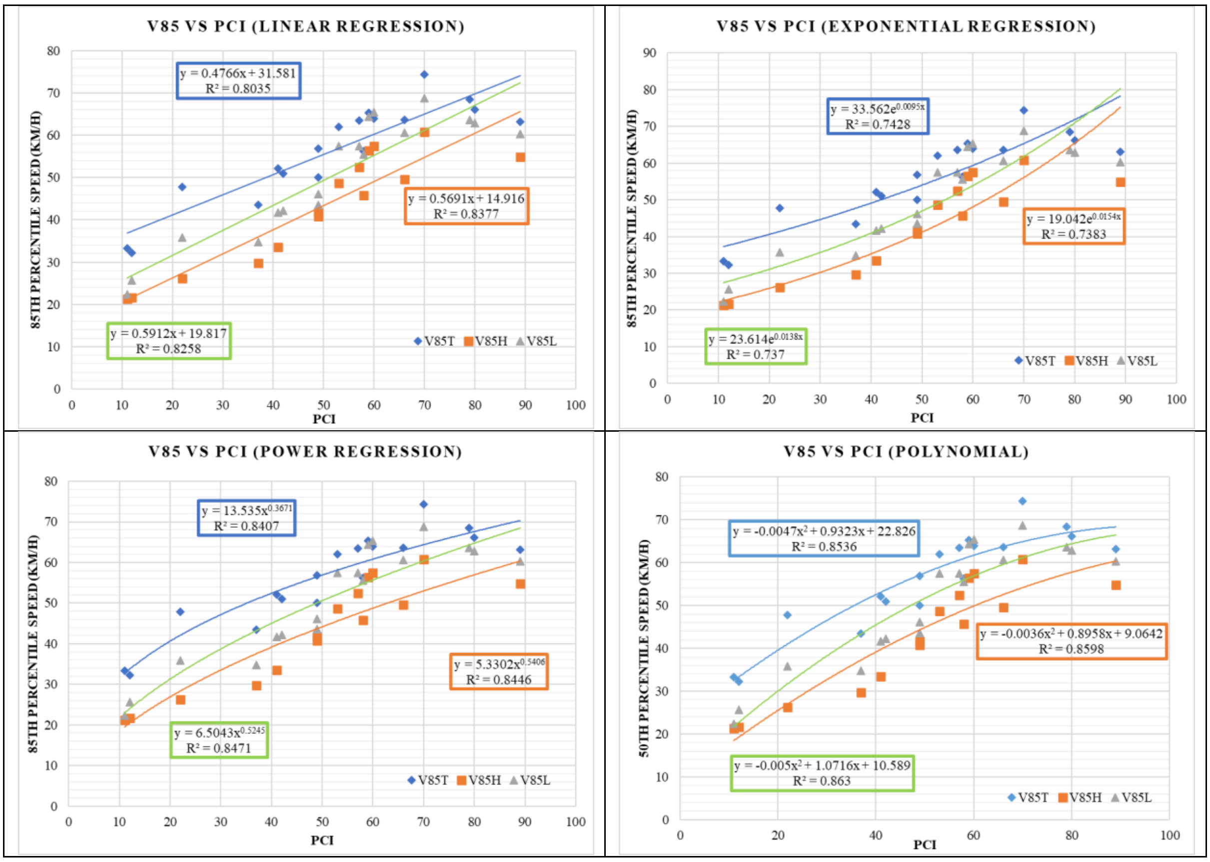


Figure 7 Speed-PCI Relationship

The study recommends the application of polynomial regression models to estimate vehicle operating speeds based on pavement condition. Equation 4 is proposed for predicting the operating speed (85th percentile speed) of two-wheelers, Equation 5 for heavy vehicles and Equation 6 for light vehicles.

$$y = -0.0047x^2 + 0.9323x + 22.826 \quad \text{.........Equation 4}$$

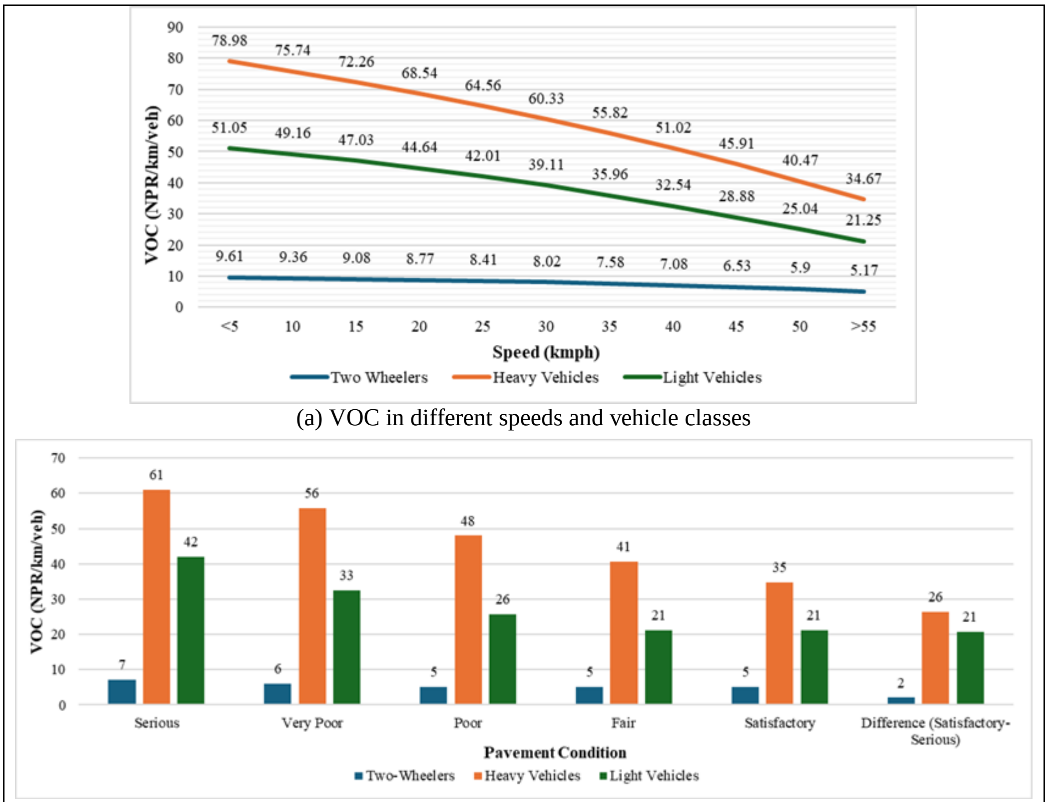
$$y = -0.0036x^2 + 0.8958x + 9.0642 \quad \text{......... Equation 5}$$

$$y = -0.005x^2 + 1.0716x + 10.589 \quad \text{......... Equation 6}$$

Where, y = 85th percentile speed and x = PCI value

3.4 Vehicle Operating Cost Analysis

The VOC, as recommended by the JICA study, was classified by vehicle types: motorcycles, cars, trucks, and buses, across various speed ranges. In this study, we adopted the VOC for two-wheelers from the motorcycle category, used the light vehicle values from the car category, and represented heavy vehicles with the average VOC values of trucks and buses. The derived VOC values for the vehicle classes utilized in this study are presented in Figure 8(a). Among the different vehicle categories, heavy vehicles show the highest VOC across all speed ranges, followed by light vehicles, while two-wheelers exhibit the lowest VOC values. Using the average 85th-percentile speeds related to various pavement condition categories (Figure 6(a)), the study estimated the VOC values through linear interpolation. The results are illustrated in Figure 8(b). The findings clearly indicate that pavement condition significantly influences operating costs, particularly for heavy vehicles. As pavement condition deteriorates from satisfactory to serious, the VOC increases progressively for all vehicle classes.



(a) VOC in different speeds and vehicle classes

(b) VOC in different pavement conditions and vehicle classes

Figure 8 Vehicle operating costs at different speeds, pavement conditions, and vehicle classes

The analysis revealed that poorer pavement conditions significantly increase VOC, especially for heavy vehicles. Compared to satisfactory pavement conditions, travelling on serious-condition roads resulted in additional operating costs of approximately:

- NPR 2 per km per vehicle for two-wheelers
- NPR 26 per km per vehicle for heavy vehicles
- NPR 21 per km per vehicle for light vehicles

The findings highlight that poor pavement conditions negatively impact heavy vehicles more than others. This is primarily due to their higher axle loads, which make them more vulnerable to surface roughness and increased rolling resistance. As a result, operating costs for these vehicles rise significantly because of higher fuel consumption, increased tire wear, more frequent maintenance requirements, and reduced travel efficiency. From an infrastructure management perspective, this underscores the economic significance of keeping roads in good condition. When roads deteriorate, user costs can increase substantially. Therefore, timely maintenance and rehabilitation of pavements are crucial. These interventions can help lower overall transportation costs, enhance network efficiency, and support sustainable road asset management strategies, especially in areas with heavy vehicle traffic.

3.5 Discussion

The selection of study segments was limited due to strict criteria designed to reduce the influence of gradient variation, intersections, roadside activities, and construction disturbances. To ensure a representative characterization of pavement distress, multiple ASTM-compliant PCI sample units were evaluated within each segment. Additionally, operating speed observations were made during isolated vehicle movements under cruise conditions, which provided a more accurate reflection of how pavement surface conditions affect vehicle speeds. As a result, the findings offer corridor-level empirical evidence that illustrates the relationship between pavement condition, operating speed, and vehicle operating costs in similar highway environments. However, it is important to interpret these relationships as indicative rather than universally applicable predictive models, as factors such as traffic composition variability, geometric characteristics, and environmental conditions may affect their relevance in different locations. Future studies should incorporate larger datasets across multiple highway corridors to enhance the reproducibility and generalizability of these findings.

4. Conclusion

This study examined how pavement surface condition affects vehicle operating speeds and costs along selected sections of the Prithvi Highway and B.P. Highway, using the Pavement Condition Index (PCI) as the main indicator of performance. Visual distress surveys following ASTM D6433 showed significant spatial differences in pavement conditions, with PCI values from 11 (serious) to 89 (excellent). Most sections fall within the poor to fair range (PCI 40–70), indicating a generally degraded pavement network needing timely maintenance. The analysis reveals a strong link between pavement condition and vehicle speed, with 85th percentile speeds decreasing as PCI drops from satisfactory (70–85) to serious (10–25). Average speeds on satisfactory pavements were about 65–70 km/h for two-wheelers, 55–60 km/h for light vehicles, and 50–55 km/h for heavy vehicles. On serious pavements, speeds declined to around 35–40 km/h for two-wheelers, 25–30 km/h for light vehicles, and 20–25 km/h for heavy vehicles. The speed reduction from good to poor pavement condition was roughly 44% for two-wheelers, 56% for light vehicles, and 60% for heavy vehicles, indicating that heavier vehicles are more affected by pavement distress.

Regression analysis showed a strong positive correlation between PCI and vehicle speed across all vehicle types. Among the models tested, polynomial regression provided the best fit, with R^2 values between approximately 0.85 and 0.86, closely followed by the power model. Linear models also explained a good portion of the variability, while exponential models were less effective. These results suggest that non-linear models, especially polynomial, better capture the speed–PCI relationship under poor and very poor pavement conditions. Based on this, polynomial regression equations are recommended for estimating vehicle speeds from PCI for different vehicle categories. Additionally, pavement deterioration significantly increases vehicle operating costs. Using JICA-recommended VOC values, traveling on serious-condition pavements adds about NPR 2 per km for two-wheelers, NPR 21 per km for light vehicles, and NPR 26 per km for heavy vehicles compared to satisfactory pavements. These higher costs are mainly due to lower speeds, increased fuel use, greater vehicle wear, and overall reduced efficiency on distressed pavements.

To conclude, the findings highlight that maintaining pavements in fair to good condition is vital not just for better traffic flow but also for reducing user expenses. The strong connection between PCI, vehicle speed, and VOC underscores the importance of considering pavement condition in highway maintenance planning and economic assessments. The results provide practical evidence supporting proactive pavement management in Nepal, helping transportation agencies allocate resources more effectively and improve economic and operational outcomes. By incorporating speed reductions related to pavement conditions into pavement management systems, agencies can develop more comprehensive maintenance prioritization strategies. This integration allows for the consideration of user costs alongside engineering performance indicators, such as the PCI. This approach can help agencies identify economically critical maintenance sections where pavement deterioration significantly impacts road user performance, especially on major freight corridors like the Prithvi Highway. While further validation using larger datasets is recommended, the relationships established in this study offer a valuable preliminary framework for integrating pavement condition with operating speed and vehicle operating cost assessments in maintenance decision-making.

5. References

Al-Masaeid, H., Sharaf, J., & Al-Suleiman (Obaidat), T. (1998). Effect of road roughness and pavement condition on traffic speed. *Road Engineering Association of Asia & Australasia Journal*, *11*, 8–14.

Arhin, S. A., Williams, L. N., Ribbiso, A., & Anderson, M. F. (2015). Predicting pavement condition index using international roughness index in a dense urban area. *Journal of Civil Engineering Research*, *5*(1), 10–17.

Ben-Edigbe, J. (2010). Assessment of speed-flow-density functions under adverse pavement condition. *International Journal of Sustainable Development and Planning*, *5*(3), 238–252.

Chandra, S. (2004). Effect of Road Roughness on Capacity of Two-Lane Roads. *Journal of Transportation Engineering*, *130*(3), 360–364. https://doi.org/10.1061/(ASCE)0733-947X(2004)130:3(360)

Haj-Ismail, I. A. (1989). *The effect of roadway surface conditions on traffic speed during day and night operations*. Texas A&M University.

Haryati, N. W., Mahendra, M. M., & Murtiadi, S. (2023). Pavement Condition Index (PCI) Analysis In Measuring Road Damage Levels and Its Effect on Vehicle Speed in Lembar-Sekotong-Lombok Barat Road Segment. *SITEKIN: Jurnal Sains, Teknologi Dan Industri*, *20*(2), 454–463.

Hashim, I. H., Badawy, R. M., & Heneash, U. (2023). Impact of Pavement Defects on Traffic Operational Performance. *Sustainability*, *15*(10), 8293. https://doi.org/10.3390/su15108293

Hashim, I. H., Younes, M. A., & El-hamrawy, S. A. (2018). Impact of pavement condition on speed change for different vehicle classes. *American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS)*, *43*(1), 271–290.

Highway Management Information System-Information & Communication Technology (HMIS-ICT) Unit. (2022). *Traffic, Surface Distress and Road Roughness Surveys on Strategic Road Network*.

Japan International Cooperation Agency (JICA). (2017). *The Project on Urban Transport Improvement for Kathmandu Valley*.

Japan International Cooperation Agency (JICA). (2023). *Preparatory Survey for Koteshwor Intersection Improvement Project*.

Kalika, S., Marsani, A., & Adhikari, D. (2021). Pavement Condition Index for Airports: A Case Study of Simara Airport. *Proceedings of 10th IOE Graduate Conference*, *10*, 279–287.

Karan, M. A., Haas, R., & Kher, R. (1976). Effects of pavement roughness on vehicle speeds. *Transportation Research Record*, (602).

Karim, F. M. A., Rubasi, K. A. H., & Saleh, A. A. (2016). The Road Pavement Condition Index (PCI) Evaluation and Maintenance: A Case Study of Yemen. *Organization, Technology and Management in Construction: An International Journal*, *8*(1), 1446–1455. https://doi.org/10.1515/otmcj-2016-0008

Khadka, R., Negi, C. S., & Pali, P. (2025). Failure and Maintenance of Flexible Pavement: A Case Study of Mahendranagar City Roads, Nepal. *Journal of NAST College*, *1*(1–2), 77–90. https://doi.org/10.3126/jonc.v1i1-2.89108

Khan, I., Khattak, K., Khan, Z. H., & Gulliver, T. A. (2023). Impact of road pavement condition on vehicular free flow speed, vibration and in-vehicle noise. *Science, Engineering and Technology*, *3*(1), 1–8.

Mahendra, R., Asih, V., Suwandi, P. A. P., & Yudaningrum, F. (2022). Analysis of Vehicle Operating Costs using Method (Pacific Consultant International) PCI on Semarang Toll Road Section and non-Toll Road (Krapyak-Jatingaleh). *International Journal of Sustainable Building, Infrastructure and Environment (IJOSBIE)*, *3*(1).

Piryonesi, S. M., & El-Diraby, T. E. (2020). Data analytics in asset management: Cost-effective prediction of the pavement condition index. *Journal of Infrastructure Systems*, *26*(1), 04019036.

Raccagni, S., Ventura, R., & Barabino, B. (2024). Impact of urban road characteristics on vehicle speed: Insights from Brescia, Italy. *Heliyon*, *10*(20). https://doi.org/10.1016/j.heliyon.2024.e39459

Robbins, M., & Tran, N. (2015). *Literature Review: The Impact Of Pavement Roughness On Vehicle Operating Costs*.

Setyawan, A., & Kusdiantoro, I. (2015). The effect of pavement condition on vehicle speeds and motor vehicles emissions. *Procedia Engineering*, *125*, 424–430.

Shahin, M. Y. (1994). *Pavement management for airports, roads, and parking lots*.

Shirazinejad, R. S., & Dissanayake, S. (2020). Speed Characteristics in Relation to Speed Limit Increase and Its Influence on Driver's Speed Selection Behavior. *Sustainability*, *12*(4), 1369. https://doi.org/10.3390/su12041369

Shrestha, J., Shahi., T. C., & Bajracharya, N. (2025). Analysis of Fatigue and Rutting Behavior of Flexible Pavement: A Case Study of Taudaha-Pharping Road. *Journal of Transportation Systems*, *10*(2), 43–55. https://doi.org/10.46610/JoTS.2025.v010i02.004

Shrestha, S., & Khadka, R. (2021). Assessment Of Relationship Between Road Roughness and Pavement Surface Condition. *Journal of Advanced College of Engineering and Management*, *6*, 2021. https://doi.org/10.3126/jacem.v6i0.38357

Shrestha, S., Pradhananga, R., Thapa, S. K., Thapaliya, S., & Shrestha, A. R. (2024). Assessment of relationship between asphalt concrete pavement performance indicators: pavement condition index and RoadRoid based international roughness index. *International Journal on Engineering Technology*, *1*(2), 191–201.

Standard, A. (2003). D6433 (2007), Standard practice for roads and parking lots pavement condition index surveys. *ASTM International*.

Wang, T., Harvey, J., Lea, J., & Kim, C. (2014). Impact of Pavement Roughness on Vehicle Free-Flow Speed. *Journal of Transportation Engineering*, *140*(9). https://doi.org/10.1061/(ASCE)TE.1943-5436.0000689

Yu, B., & Lu, Q. (2014). Empirical model of roughness effect on vehicle speed. *International Journal of Pavement Engineering*, *15*(4), 345–351.