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Post-Disaster Analysis of Road User Cost – A Case Study of BP Highway(NH13)

by

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The undersigned certify that they have read and recommended to Institute of Engineering for acceptance, a thesis entitled **"Post-Disaster Analysis of Road User Cost – A Case Study of BP highway (NH13)"** submitted by Shankar Khanal in partial fulfillment of the requirement for degree of Master of Science in Transportation Engineering.

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ABSTRACT

This study evaluates the impact of post-disaster disruptions on Road User Costs (RUC) along the Dhulikhel–Barkhekhola section of the BP Highway (NH13), which was severely damaged by floods and landslides in September 2024. A calibrated HDM-4 model was used to assess Vehicle Operating Costs (VOC), Travel Time Costs (TTC), and total RUC under both pre- and post-disaster conditions. Before the disaster, the entire section consisted of continuous bituminous pavement. After the disaster, the road was divided into two distinct segments: an 8.53 km detour and a 37.33 km unaffected (bituminous) section. Each segment was analyzed separately, and a weighted average was computed to represent the overall post-disaster scenario of the 45 km route.

Results reveal that the 8.53 km gravel detour (19% of the route) increased annual VOC, TTC, and RUC by NPR 12.39 million/km, NPR 4.79 million/km, and NPR 17.19 million/km, respectively yielding total increased of NPR 773.55 million across 45 km stretch, with fuel costs contributing 30% to the rise. Sensitivity analysis identified traffic volume, road roughness (IRI), and geometric factors (gradient, curvature) as critical cost drivers. Upgrading detours to bituminous surfaces reduced annual RUC by NPR 16.3 million/km, yielding total savings of NPR 733.5 million across the 45 km stretch.

These findings highlight the importance of resilient infrastructure and timely road surface maintenance to minimize economic losses and support post-disaster recovery. This study urges policymakers to prioritize maintenance and upgrades to minimize economic losses in Nepal's road-reliant transport system.

Keywords: Road user cost, Vehicle operation cost, Travel time cost, Highway Development and management model

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ABBREVIATIONS

VOC	Vehicle Operation Cost
TTC	Travel Time Cost
RUC	Road User Cost
DoR	Department of Road\
HDM	Highway Development and Management Model
G/C	Gradient/Curvature
IRI	International Roughness Index

CHAPTER 1: INTRODUCTION

1.1 Background

Road User Costs (RUC) represent the expenses incurred by individuals and businesses while utilizing road networks. These include Vehicle Operating Costs (VOC), Travel Time Costs (TTC), and Accident Costs (ACC). Together, they constitute the most substantial portion of the total life-cycle costs of road infrastructure projects, often exceeding 90% for high-traffic roads. Unlike the construction and maintenance costs borne by road agencies, RUC is shouldered directly by users.

The significant components of the RUC are as follows.

1. **Vehicle Operating Costs (VOC):** These include fuel, spare parts, tire wear, depreciation, and labor costs for vehicle operation.
2. **Travel Time Costs (TTC):** This represents the economic value of time lost during travel, which could otherwise be utilized for productive purposes.
3. **Accident Costs (ACC):** Encompass expenses related to injuries, fatalities, property damage, and associated medical care.

RUC calculations are critical for economic feasibility studies, road maintenance planning, and policy making in the transportation sector. For instance, in Bangladesh, the annual RUC for 2004 was estimated at Taka 389 billion in economic terms and Taka 512 billion in financial terms, accounting for 15% of the GDP for 2003-04. Such high costs underscore the importance of effective maintenance and management of road networks to minimize VOC and TTC, improve road safety, and enhance economic efficiency.

Using models like HDM-4, RUC studies integrate data from field surveys, vehicle operator reports, and accident statistics. Calibration of models ensures accurate predictions tailored to local conditions, aiding in the optimization of road maintenance investments and traffic management strategies. Properly addressing RUC not only reduces economic burdens but also fosters sustainable transport development (Road User Costs Report, Bangladesh 2004-2005).

1.2 Problem Statement

In Nepal, road infrastructure, especially highways, frequently suffers significant damage following monsoon seasons or natural disasters. Despite the severity of such damage, many affected roads remain in poor condition for extended periods mainly due to limited resources and less prioritization in road maintenance by government agency. As a result, highway surfaces often degrade from bituminous to untreated gravel and are left unrepaired for longer time.

This lack of timely maintenance imposes a substantial burden on road users. Among the various impacts, the economic burden is particularly prominent. Increased vehicle operating costs (VOC), longer travel times, and reduced safety collectively raise the overall Road User Cost (RUC), affecting both individual users and the broader economy.
Quantifying RUC is essential to capture the direct economic consequences of delayed maintenance and degraded road conditions. Highlighting these costs can provide valuable insights for policymakers, enabling them to prioritize effective road maintenance, post-disaster restoration, and strategic investment in resilient infrastructure

1.3 Objective of Study

The main objective of the study is to assess the impact of disaster on road user costs along Dhulikhel-Barkhekhola section of BP Highway (NH13). The specific objectives are enlisted as below:

1) To quantify road user costs (RUC) before and after the disaster using HDM-4 model and identify critical factors influencing road user costs.
2) To recommend improvement measures for minimizing road user cost under post disaster condition.

1.4 Limitation of Study

The project report was prepared under following limitations:

1) When quantifying road user costs before and after the disaster, it is assumed that the total traffic volume remains unchanged during both periods.

2) While accident costs are an integral component of road user costs, they were excluded from the scope of this study

1.5 Organization of Report

The project report consists of four chapters as follows:

Chapter 1: Introduction Provides context on Road User Costs (RUC), outlines the significance of BP Highway, and defines study objectives, scope, and limitations.

Chapter 2: Literature Review Explores RUC frameworks, HDM-4 applications, and disaster-related cost studies.

Chapter 3: Methodology Describes data collection, HDM-4 calibration, and damage assessment techniques.

Chapter 4: Results and Discussion Analyzes cost increases (VOC, TTC, RUC) and their implications for users and the economy.

Chapter 5: Conclusion and Recommendations Summarizes findings.

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CHAPTER 2: LITERATURE REVIEW

2.1 Road User Cost

Road user costs may be defined as the costs incurred by vehicle operators and by the travelling public at large. The four types of road user costs usually considered are associated with vehicle operation, travel time, accidents and discomfort. The last two costs are difficult to quantify in monetary terms, although accident costs can be estimated in several ways in terms of both the resource content (for example, cost of spares and vehicle replacement), and the injuries and fatalities. However, the lack of acceptable methods of estimating accident and discomfort costs in developing countries is the main reason why these two components of road user costs are not included in existing road investment appraisal models for developing countries. (HDM Documentation, Henry G. R. Kerali)

Vehicle Operating Costs are calculated from the sum of the vehicle resources components including

- Fuel and lubricating oil consumption,
- Tyres and spare parts,
- Vehicle maintenance labour costs,
- Vehicle crew wages,

Separate sets of equations are used for the different vehicle types specified by the user. For each vehicle type, the models predict average travel speeds as a function of road geometry and road condition. The above VOC components, with the exception of vehicle depreciation and interest, depend largely on road roughness and the geometric characteristics of the road. The consumption of the above VOC components is predicted in resource terms. For example, the equations for fuel consumption calculate the quantity of fuel consumed over a travel distance. Unit costs for the various resources are specified by the user in order to calculate the annual total costs of vehicle operation. Vehicle depreciation is considered to be a function of the predicted travel time and of the level of vehicle utilization. (HDM Documentation, Henry G. R. Kerali)

Travel time costs are calculated from average vehicle speeds, travel distances and the unit costs per hour of road users' time. The average vehicle speeds are a function of road roughness, road width, and the vertical and horizontal alignment of the road. The values to be specified for unit time costs for road users in developing countries are not easily justifiable. Many authors on this subject recommend that projects in developing countries should be appraised without benefits from time savings. The road user benefits derived from savings in travel time costs can in this case be considered to be a "consumer surplus" in addition to the savings in VOC.

2.2 Highway Development and Management Model (HDM-4)

HDM-4 is a widely used computer model that simulates physical and economic conditions over the period of analysis, usually a life cycle, for a series of alternative alternatives and scenarios specified by the user (Bennett & Paterson, 2002).

The Highway Development and Management Model (HDM-4) is software for investigating investment choices on different types of roads including flexible, rigid and unsealed pavements. It can assist road managers to predict future economic, technical, social and environmental outcomes of possible investment thus making consistent and defensible decisions. Highway Design and Maintenance Standard Model (HDM-III), the predecessor of HDM-4, developed by World Bank, has been used for more than 20 years. HDM-4 was released in version 1.0 in March 2000, with an updated version 1.2 issued in August 2000.

2.2.1. Applications of HDM -4

HDM-4 is a powerful system for the analysis of road management alternatives. With different application tools (Project, Program and Strategy), HDM-4 can be applied in the following 4 areas (Kerali, et al., 2002).

2.2.1.1. Project Analysis

This function can be performed using HDM-4 project analysis application tool. Project analysis can evaluate road projects or investment options. Road sections with user-selected treatments are analyzed over a specified period and the pavement performance, life cycle costs and user costs can be predicted to compare the different investment options. The main outputs include:

- Predictions of road deterioration, maintenance effects and costs.
- Road user costs and benefits.
- Economic comparisons of project options in terms of Net Present Value (NPV) and Estimates of environmental effects.

Typical projects include pavement maintenance and rehabilitation, road widening, geometric improvement, pavement upgrading and new construction.

2.2.1.2. Program Analysis

This function can be performed using HDM-4 program analysis application tool. The program analysis is concerned with preparation of a multiyear road works and investment programs under budget constraint. The road sections requiring treatments are identified and prioritized in short or medium term. Then, a budget for one or rolling multiyear work program for a road network is provided.

2.2.1.3. Strategy Analysis

This function can be performed using HDM-4 strategy analysis application tool. Strategy analysis is concerned with analysis of a chosen network as a whole, for preparing long range planning estimates of expenditure needs for road development and construction under different budget scenarios for medium to long term periods of 5-40 years. The road network is characterized by length of road in different categories defined by parameters such as road class, surface type and pavement condition or traffic flow. It also forecasts of pavement performance and road user costs.

2.2.1.3. Research and Policies Studies

HDM-4 can be used to conduct a number of road sector policy studies including:

- Funding policies for competing needs; for example, feeder roads versus main roads.
- Road user charges for setting up road funds.

- Impact of road transport policy changes on energy consumption.
- Impact of axle load limits. - Pavement maintenance and rehabilitation standards.

The underlying operation of Project, Program and Strategy analysis in HDM-4 is similar. In each case, HDM-4 analyses the life cycle costs, which include capital investment, maintenance and road user costs, during the user-specified period. Costs are determined by amount of consumed resources multiplied by unit cost. Then, HDM-4 can compare different investment options using the total costs incurred in each option

2.2.2. HDM Models

There are four models built in HDM-4 to calculate and analyze the input data in each application. Each model has many sub-models (Kerali, et al., 2002). HDM-4 uses 'deterministic' model which predicts a single future output depending upon the current situation.

2.2.2.1. Road Deterioration Model (RD)

The relationships in the model are formulated based on mechanistic concepts of material properties and behaviors under traffic and climatic factors and the results of experimental research. Thus, the model is flexible and can be applied in a wide range of countries. It can predict the annual deterioration of each type of pavement under the action of axle loads and environmental effects, using structural condition and distress measures specific to each pavement type. Each measure has a sub-model.

- Bituminous pavement distress measures include cracking, rutting, raveling, potholes, edge break and roughness.
- Concrete pavement distress measures include cracking, faulting, spalling, failure, serviceability loss and roughness.
- Unsealed pavement distress measures include loss of gravel and roughness.

2.2.2.2. Works Effects Model

It implements road works programs and determines work costs and effects specific to each pavement type. First, it selects works to do from a range of standard maintenance works, which include routine maintenance, periodic maintenance, rehabilitation and reconstruction works; or selects works from a range of standard improvement work types, which include widening, full reconstruction with minor widening, realignment, off carriageway works; or it selects construction works, which include upgrading and new road section construction. Then, using the relationships and equations built in the model, works effects model can predict the costs and effects of undertaking the works.

2.2.2.3. Road User Effects Model

It includes some sub-models such as free speed model, fuel consumption model, speed-flow model and parts consumption model. When inputting data, vehicles are selected or defined from the standard types. Then road user effects model can use the specified physical, performance, energy and cost characteristics for vehicles in the selected vehicle fleet to predict:

- The performance and operating costs of motorized and non-motorized vehicles for the various project, program or strategy options included in the study.
- Travel time costs according to passenger travel and cargo holding time.
- The accident costs using user defined accident rates and unit costs.
- The effects of interaction between motorized and non-motorized traffic streams.
- The savings of road users by choosing different investment options

2.2.2.4. Safety Energy and Environmental Effects(SEE) Model

The model has the following two functions: - Predicts the life cycle energy consumption of different investment options considering maintenance and construction works and vehicle operations. Then, it can compare these investment options. - Predict vehicle emissions and change in environmental effect when choosing between investment option.

2.2.3. HDM -4 Calibration

HDM-4 simulates the future changes in the road system from current conditions (Morosiuk & Kerali). In order to use the model correctly, one needs to ensure that HDM is suitably calibrated. Hence, the calibration of HDM-4 model is needed in order to enable the model represent the reality of conditions and influencing factors of the region as well as to fit the real behavior and interactions between various factors for the variety of conditions to which it is applied.

There are three levels of calibration of HDM which involve low, moderate and major level of efforts and resources. In terms of effort the following three levels can be reviewed as weeks, months and years respectively (Bennett & Paterson, 2002).

2.2.3.1. Level 1 – Basic Calibration

Table 2.1: Level 1- Basic calibration parameters

Road User Effects (RUE)	VOC components, such as vehicle prices, tyre cost, fuel and lubricant prices; vehicle utilization, service life, annual hours driven, utilization method; travel time cost, i.e. passenger time: work and non-work, crew and cargo cost, maintenance labour, interest rate, overhead cost, etc.
Road Deterioration Work Effects (RDWE)	Unit costs of various elements for interventions: improvement and maintenance, policy and strategy; cracking initiation and progression factor, ravelling initiation and progression factor, rut depth progression factor, construction quality indicators.
Vehicle Characteristics	Representative vehicles and their characteristics, i.e., number of axles, number of tyres, tyre type, wheel diameter, operating weight and axle loading; aerodynamic drag coefficient and projected frontal area, braking power, vehicle driving and breaking power.
Economic Analysis Data	Discount rate, analysis period, salvage value and related data;
Pavement Characteristics	Pavement type, material characteristics, pavement condition data and other surface distress data;

Motorized and Non-Motorized Traffic	Classified traffic volume data, hourly distribution of traffic, annual traffic growth rates including divertible, generated and induced traffic, speed limit, capacity and speed flow type, traffic flow pattern.
Accident Class	Rate of fatal, injury and damage accidents
Climate Class	Tropical, sub-tropical, temperate, etc.

Source: HDM-4 Documentation

2.2.3.2. Level 2 – Calibration

Table 2.2: Level 2- calibration parameters

Pavement Deterioration Models	Adjusting parameters related to pavement roughness, cracking, and rutting to match observed deterioration patterns in the local environment1
Road User Effects	Calibrating factors such as vehicle operating costs, fuel consumption, and emissions based on local traffic conditions and vehicle fleet characteristics1
Maintenance Effects:	Fine-tuning the impact of different maintenance activities on pavement performance, including the effectiveness and costs of various maintenance treatments1
Traffic Loading	Adjusting the model to account for local traffic volumes and axle load distributions, which can significantly affect pavement deterioration1

Source: HDM-4 Documentation

2.2.3.3. Level 3 – Adaptation

Undertakes major field surveys and controlled experiments to enhance the existing predictive relationships or to develop new and locally specific relationships for substitution in the source code of the model. This consists of long-term researches and studies conducted under local conditions to develop alternative functions. Research like pavement deterioration is a long-term endeavor, typically requiring a minimum of 5 years. Every HDM analysis requires at least a Level 1 calibration. Not much of work has been conducted in Nepal in the field of Level 3 calibration of HDM-4 model, hence the level 3 calibration factors used during the preparation of Priority Investment Plan (PIP) by DoR in 2007 and during the preparation of master plan 2024 are mostly applied in this study. Level 1 calibration lies within the scope of the study.

2.2.4. HDM-4 Output

HDM-4 supports flexible options for data and analysis results. Users can make printed or electronic reports. They can also export data and results to standard database for other users. The file formats are not limited to text and word documents, but can also be taken in MS excel spread sheets. In addition, users have direct access to the result database files (DBF). HDM-4 can produce the following three types of output, which can assist road managers to make informed decisions:

- Economic efficiency indicators: produced from analysis of individual road projects.
- Multi-year work programs: produced from prioritization of several road projects.
- Strategic road maintenance and development plans: produced from long-term predictions of road network performance.

2.2.5. HDM-4 Applications in Nepal

HDM-III was applied for the calculation of Road User Costs and preparation of long-term periodic maintenance plans under Nepal Road Maintenance Project in 1991 AD by the Department of Roads (RMP, 1991). DoR carried out preparation of Feeder Road Standard for computation of threshold traffic level for feeder road upgrading in 1997 (DoR, 1997). The VOC model prepared in 1991 was modified in 2001 by using the upgraded HDM-4 (MRCU-RUC, 2001). Another remarkable use of HDM-4 software was during the preparation of Priority Investment Program (PIP) in 2007 for setting a 10-year expenditure plan and strategy on road maintenance, improvement and new construction. Some parameters of HDM-4 were calibrated to make the model compatible with the local condition during the same time (PIP, 2007). HDM-4 is being used in upcoming donor supported projects such as MCC supported road upgrades. Furthermore, the HDM-4 model was recently used in the preparation of Nepal's Road Master Plan in 2023, which served as the foundational basis for the Priority Investment Plan (PIP) 2024.

CHAPTER 3: METHODOLOGY

3.1 Research Design

This study adopts a quantitative approach to assess the impact of the September 2024 disaster on road user costs (RUC) along the Dhulikhel-Barkhekhola section of BP Highway (NH-13). The research integrates field surveys, secondary data, and the Highway Development and Management Model (HDM-4) to quantify changes in Vehicle Operating Costs (VOC), Travel Time Costs (TTC), total RUC and average vehicle operating speed before and after the disaster. The methodology follows three phases:

- Data Collection: Field surveys, primary and secondary data compilation.
- Model Calibration: Configuring HDM-4 with local parameters.
- Scenario Analysis: Comparing RUC, Vehicle operating speed pre- and post-disaster, evaluating mitigation measures

The workflow is illustrated in Figure 3. 1.

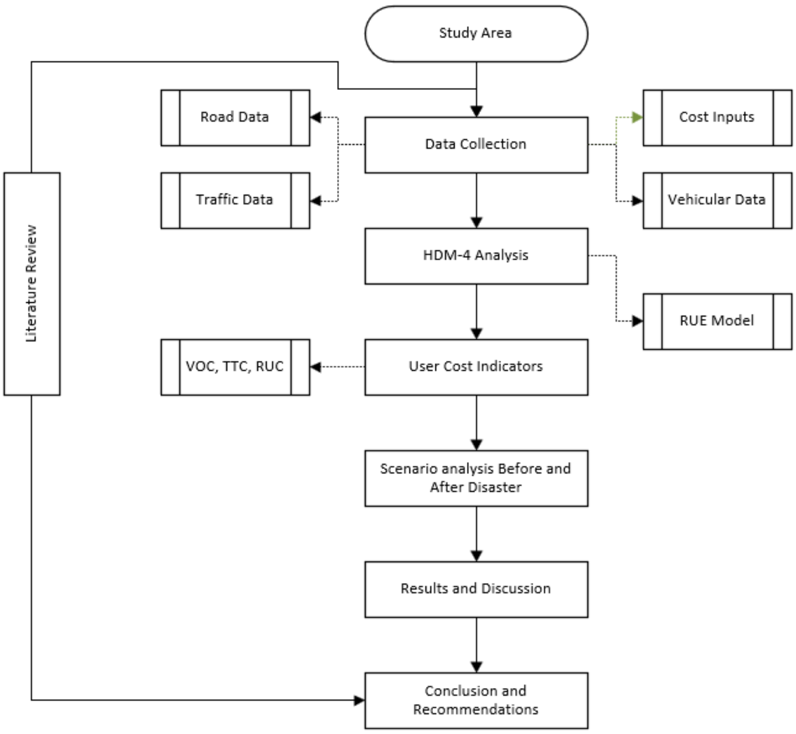

Figure 3.1: Research design flow chart

3.2 Study Area

The 45 km Dhulikhel-Barkhekhola stretch of the BP Highway traverses Nepal's central hills, characterized by steep slopes and unstable sedimentary rock layers like sandstone and shale. Severe late September 2024 floods triggered landslides, slope failures, and riverbank erosion, causing extensive road washouts. Critical zones like Piple and Sindhuli Bazar exhibit collapsed embankments, and road surface degradation, including potholes, longitudinal cracks, and asphalt erosion exacerbated by sediment-laden runoff. Total 18 temporary diversions, primarily gravel-based emergency bypasses, were created to maintain traffic flow around high-risk landslide zones and collapsed sections. The alignment from Dhulikhel to Barkhekhola is shown in the figure 3.2 below:

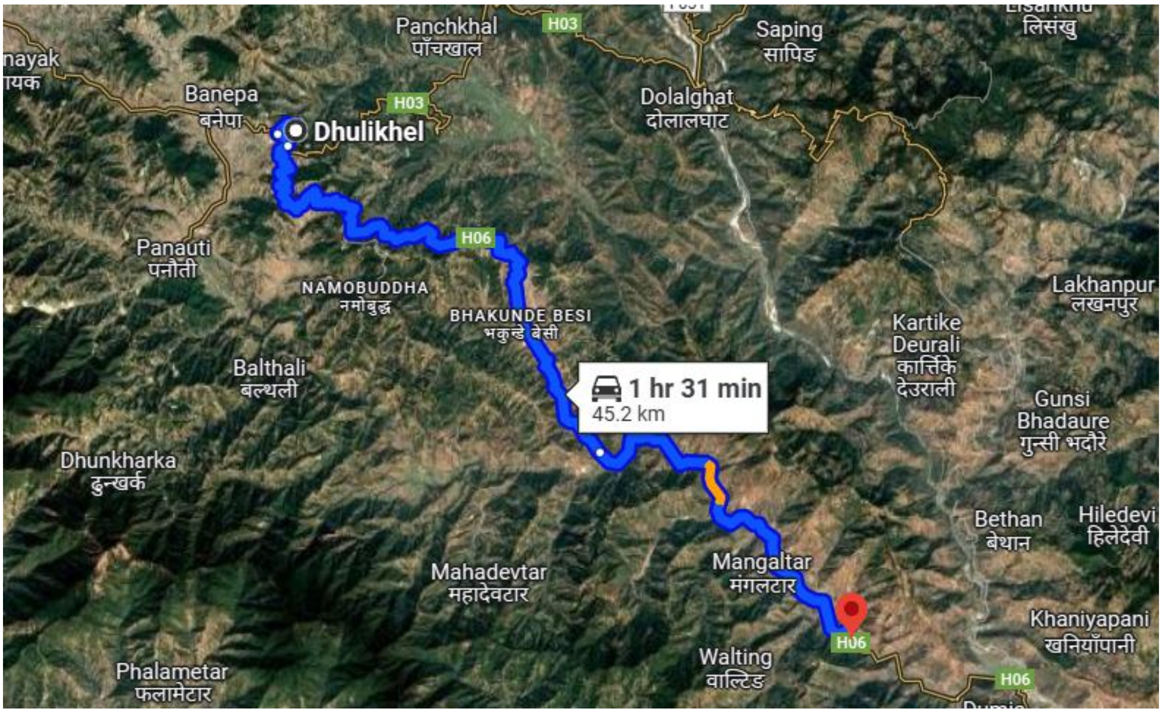

Figure 3.2: Study area: Dhulikhel-Barkhekhola section of BP highway(NH-13)

3.2.1 Brief Introduction to BP Highway

The Banepa-Bardibas Highway, popularly known as BP Highway, is an important transport corridor connecting central hills of Nepal with the Terai Plains. It runs from 158 kilometers from Banepa, situated in the Kavrepalanchok district, through Bardibas to the Mahottari district. This highway is significant in promoting economic development, cultural integration, and modernization. It greatly reduces the distance of travel between Kathmandu and eastern Nepal by around 200 kilometers, allowing many daily travelers, including emergency evacuations and disaster relief operations, especially in Kathmandu, which is a seismically active region. The map of BP highway sections that are affected by heavy rainfall is shown in figure 3.3.

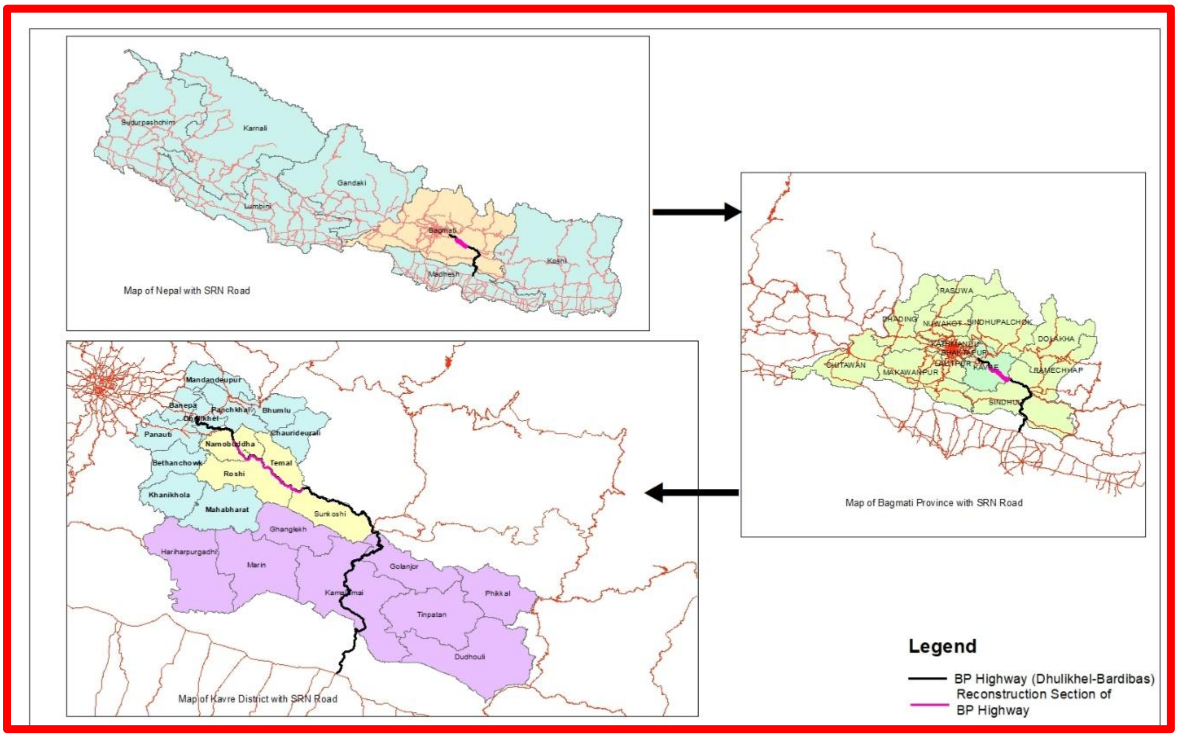

Figure 3.3: BP Highway with sections affected by heavy rainfall.

3.3 Data Collection

The field assessment was conducted through detailed site visits and visual inspections. Data collected during the site visits included measurements of the affected areas, detailed observations of the damage, traffic data, and IRI measurements at 100-meter intervals. This information was essential for providing an accurate analysis of the current state of the highway. HDM-4 requires a wide range of data related to the road section, vehicle attributes and traffic data. The road section data including rise+fall, average horizontal curvature, section length, average carriageway width, shoulder width, superelevation and IRI were obtained from field survey. Traffic data were taken from the Department of Roads(DoR). The data related to basic characteristics of vehicles, such as physical characteristics, utilization and loading were taken from Priority Investment Plan 2024, developed by ADB for DoR. Economic unit costs of vehicles including vehicle purchase cost, tyre cost, lubricating oil cost, maintenance labour cost, crew wages were collected from various vehicle manufacturers and vehicle service centres of Kathmandu. The economic cost of fuel was obtained from Birjung custom office and value of time cost were determined using the methodology outlined in PIP 2024.

3.3.1 Field Assessment

Out of the total 45.86 km road section, 8.53 km was observed to be fully washed out due to the disaster necessitating the establishment of 18 detours to facilitate traffic movement. The damage map of visited section is shown in the figure 3.4 below.

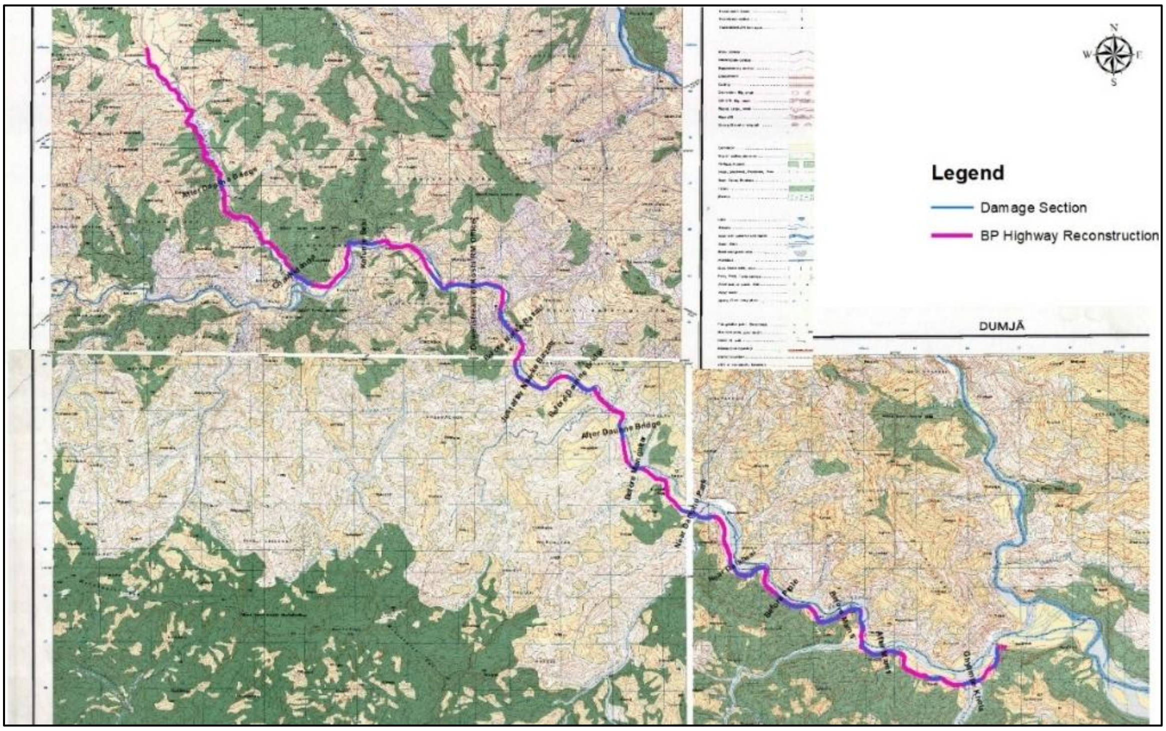

Figure 3.4: Damage map of BP highway

The lengths of each detoured segment along with their respective average IRI values are presented in table 3.1 below.

Table 3.1: Field Assessment of detour.

S/N	Chainage		Detour Length(m)	IRI
	From	To		
1	136+002.6	135+688.6	274.5	22.70
2	133+388.6	132+535.5	744.7	22.64

3	131+415.2	130+828.4	573.9	21.58
4	129+146.3	127+877.4	1232.2	20.48
5	127+367.4	127+033.0	306.3	23.14
6	126+823.0	126+351.2	461.8	19.95
7	125+613.3	125+172.5	376.6	23.16
8	124+188.8	124+036.5	142.3	19.89
9	122+628.1	122+263.6	354.6	19.22
10	121+753.6	121+425.6	313.2	17.77
11	120+032.5	119+526.5	485.4	19.68
12	118+616.5	117+635.4	957.4	19.00
13	116+925.5	116+451.9	455.9	22.55
14	116+341.9	116+073.1	255.3	20.84
15	115+663.1	115+204.9	448.3	20.01
16	115+194.9	114+994.2	180.4	15.78
17	114+784.3	114+356.5	365.5	19.37
18	114+046.5	113+418.9	598.1	20.75
Total length =8526.4				**Average IRI= 20.59**

Also, the actual damaged road length along the Dhulikhel Barkhekhola section of BP highway was also computed which is shown in table 3.2 below:

Table 3.2: Field assessment of damaged section.

From	**To**	**Actual damaged road Lenth (m)**
113+340.00	114+000.00	660
114+400.00	114+630.00	230
115+000.00	115+250.00	90
115+250.00	115+620.00	370
116+100.00	116+511.00	211
116+500.00	116+880.00	380
117+080.00	117+520.00	440
117+610.00	118+500.00	890
119+690.00	119+980.00	290
121+422.00	121+672.00	250
122+200.00	122+470.00	270
123+900.00	124+000.00	100
124+300.00	124+337.00	37
125+250.00	125+455.00	205
126+300.00	126+780.00	480
127+200.00	127+280.00	80
126+820.00	127+000.00	180
128+258.00	128+375.00	117
127+560.00	127+980.00	420

130+700.00	131+250.00	550
132+688.00	132+729.00	152
132+729.00	133+074.00	345
135+849.70	135+900.00	50
134+910.00	135+000.00	90
Total length		**6887**

3.4 HDM 4 Model Configuration and Calibration

Calibration involves aligning HDM-4 outputs with observed RUC data. Parameters such as Road section data, traffic data, fleet structure, vehicle utilization, loading, fuel cost, crew cost, maintenance labour cost, tyre cost and the value of time for passenger has been calibrated.

3.4.1 Road Section Data

Various data related to the road sections like length, carriageway width, shoulder width, rise and fall, surface class, superelevation, average horizontal curvature, pavement type, speed limit before and after disaster were obtained from field survey as shown in table 3.3

Table 3.3: Road section data before and after disaster

	Before disaster	**After Disaster**	
		Unaffected Section	Detoured Section
Section Length	45	37.33	8.53
Average IRI	5.87	5.87	20.59
Average Carriage width(m)	5.5	5.5	4
Shoulder width (m)	1	1	0
Flow direction	Two way	Two way	Two way
Surface Class	Bituminous	Bituminous	Unsealed
Rise+fall (m/km)	20	22.4	41
Horizontal Curvature(deg/km)	203	168	346
Superelevation (%)	3	3	5
Total AADT (pcu)	9311	9311	9311

3.4.1.1 Road Roughness Data

The IRI of the section was measured at 100-meter intervals. The average IRI of the affected and unaffected sections was computed separately. The average IRI from the previous year was obtained from the DOR website. The average IRI of the detoured section (8.53 km) was found to be 20.59, while that of the unaffected section (37.33 km) was 5.87.

3.4.2 Traffic Data

The traffic data prior to the disaster, with an AADT of 9,311 PCU, were obtained from the Department of Roads (DoR) website. Following the disaster, traffic volume on the section dropped significantly to approximately 3,000 AADT, primarily due to road damage and disruption. It is expected that the traffic will gradually recover over time as road conditions improve. Additionally, some traffic may have diverted to alternative routes, which could lead to an underestimation of actual economic losses if the reduced post-disaster traffic data are directly used in the analysis. Therefore, to maintain consistency and to assess the potential economic impact comprehensively, the post-disaster traffic volume was assumed to be the same as the pre-disaster traffic level. The road traffic data before and after disaster are presented in the table 3.4.

Table 3.4: Road traffic data before and after disaster.

Vehicle Type	Before/After Disaster
Car	1773
Heavy Truck	804
Light Truck	245
Medium Bus	735
Micro Bus	914
Small Bus	1098
Motor Cycle	2303
Three Wheeler	26
Tractor	14
Utilities	638
Jeep	761
Total	**9311**

3.4.3 Vehicle Attributes

The physical characteristics, utilization patterns, and loading specifications of the vehicle fleet were obtained from the ADB (2024) Priority Investment Plan. Physical attributes include passenger car space equivalents (PCSE), number of wheels and axles, tyre type, base number of recaps and retread costs. Utilization parameters cover average annual kilometers traveled, operating hours, vehicle lifespan, proportion of private use, average number of passengers (excluding crew) and the percentage of work-related passenger trips. Loading characteristics, such as Equivalent Single Axle Load Factor (ESALF) and operating weight, are also detailed. All related values are presented in Appendix 1: Vehicle Fleet.

Fleet specifications along with associated costs were sourced from the NADA Automobile Association of Nepal. A detailed economic cost breakdown for each vehicle type is provided in Appendix 3: Vehicle attributes; economic cost.

3.4.4 Fuel Cost

The fuel cost build-up is based on data collected in March 2025 from the Birgunj Customs Office. This exercise aims to calculate the economic cost of petrol and diesel in Nepal. The taxes identified in the fuel pricing structure include import duty, infrastructure tax, road construction fund, government tax, and Value Added Tax (VAT).

To assess the tax components for both products, relevant documents (Bhansar Pragyapan Patra) were obtained from the Birgunj Customs Office. The analysis reveals the economic cost of petrol as NRs. 105 per litre and the economic cost of diesel as NRs. 95 per litre as shown in table 3.5.

Table:3.5: HDM 4 calibration: Fuel cost build up

S. N.	Description	Petrol	Diesel
1	Cost of fuel at Birjung Bhansar(excluding all taxes, duties and levies)	92.32	87.07
2	Retailers Operating Margins	6.3	5.02
3	Transport Charges (Local)	6.58	3.17

4	**Economic Cost (Excluding Taxes, Duties & Levies) (1+2+3)**	**105.2**	**95.26**

3.4.5 Crew Cost

The estimation of crew costs has been developed based on a detailed survey conducted at various vehicle service centers located in and around the Kathmandu area. The results of this survey are summarized in the table 3.6 below

Table:3.6: HDM 4 Calibration: crew cost builds up

			NRs				
S/N	Particular	Unit	4WD/LV	BUS		Trucks	
				Light	Large	Heavy	V-Heavy
1	Driver (salary +levy)	Monthly	30000	50000	56000	65000	65000
2	Assistant	Monthly		28000	30000	15000	15000
3	Other Crew Cost	L.S.				25000	25000
4	Crew Performance	hrs/day	8	9	9	12	12
5	Work Days	Monthly	25	25	25	15	15
6	Crew Performance (4*5)	hr/month	200	225	225	180	180
7	Crew Cost	NRS/hr	**150**	**347**	**382**	**583**	**583**

3.4.6 Maintenance Labour Cost

The maintenance labour cost was assessed based on data collected from various vehicle service centers. An average value was then derived from the surveyed rates to represent a realistic estimate of labour charges as shown in table 3.7

Table:3.7: HDM 4 Calibration: Maintenance labour cost

Particular		Unit	Adjusted Cost (NRs)
Labor	Skilled	NRs/month	46,000
	Semi-Skilled	NRs/month	39,000
Normal Work Hours		hr/month	200
Workshop Labor (skilled)		NRs/hr	230

Workshop Labor (semi-skilled)	NRs/hr	195
Labor Input (skilled)	Hr/assignment	5.5
Labor Input (semi-skilled)	Hr/assignment	8.0
Total Labor inputs	Hr/assignment	13.5
Labor Cost (skilled)	NRs/assignment	1,265.0
Labor Cost (skilled)	NRs/assignment	1,560.0
Total Labor inputs	NRs/assignment	2,825.0
Total Labor inputs	NRs/hr	209.3
Workshop Overhead, etc.	NRs/hr	10.46
Total Workshop Labor Cost	**NRs/hr**	**220**

3.4.7 Tyre Cost

Cost build-up exercise for various types of tyres used in BP highway vehicle fleet has been conducted. For this purpose, major tyre dealerships in Kathmandu including Apolo Tyres and Shubhashree Tyres (located in Teku) were taken. Sales departments of the selected dealerships were contacted to gather data on market prices of different tyre types and the breakdown of taxes, duties, and other components embedded in their pricing.

Through these discussions, detailed information on pricing structures and fiscal impositions (e.g., import duties, VAT) was obtained. Based on this data, the economic costs of various tyre categories have been calculated as shown in table 3.8

Table:3.8: HDM 4 Calibration: Tyre cost build up

Tyre Size	Vehicle Type	Financial	Custom Duty	VAT	Economic
600-16	Cars & LVs	6,800	20%	13%	5,015
195-R14	Cars & LVs	9,100	20%	13%	6,711
700-15	4-WD Pickups	15,000	20%	13%	11,062
750-16	4-WD Pickups	21,800	20%	13%	16,077
650-20	4-WD Pickups	10,100	20%	13%	7,448
750-R16	4-WD Pickups	10,550	20%	13%	7,780
750-16 LD	Light Trucks & Buses	21,100	20%	13%	15,560
750-16 RA	Light Trucks & Buses	21,800	20%	13%	16,077
900-20 MA	Medium Trucks	39,600	20%	13%	29,204
1000-R20 MA	Medium and Heavy Trucks	39,600	20%	13%	29,204

1000-R20 326	Medium and Heavy Trucks	40,600	20%	13%	29,941
1000-R20 LD	Medium and Heavy Trucks	41,100	20%	13%	30,310
1100-R20 LD	Heavy Truck & Buses	45,500	20%	13%	33,555
1100-R20 RA	Heavy Truck & Buses	42,800	20%	13%	31,563
1200-R20	Heavy Truck & Buses	38,100	20%	13%	28,097
1200-R21	Heavy Truck & Buses	46,100	20%	13%	33,997

3.4.8 Value of Time Cost

The value of time for passenger were determined using the methodology outlined in PIP 2024 which is based on macro-economic performance indicators such as per capita GDP, employment ratio, consumption expenditure; and the outcomes of the trip ratio in terms of travel for working purpose and travel for non-working purpose. The working of passenger travel time with data inputs and corresponding sources is illustrated in Table 3.9.

Table 3.9: Estimation of Passenger Travel Time (NRs.)

S.N.	Particular	2023-24	Source/Remarks
1	Per Capita Income (Current GDP/ Population)	193,590	Economic Survey 2023/24
2	Employment Ratio (%)	35.57%	World bank report
3	Per Capita Income (Employed Persons)	552,600	=(1)/(2)
4	Consumption Expenditure w.r.t. GDP (%)	92.4%	Economic Survey 2023/24
5	Income–Employed / Person	510,602	=(3)*(4)
6	Working Hours (Annual)	2,000	DoR Master Plan 2024
7	Average Working Time Travel (NRs./hr)	**255**	= (5)/(6)
8	Non-Working Time Travel (NRs./hr)	**64**	=(7) 25% of the average working travel time.

3.5 RUC Comparison Before and After Disaster

A comparative analysis was carried out to evaluate the Road User Cost (RUC) and vehicle operating speeds before and after the disaster event. This analysis included key components such as vehicle operating cost, travel time cost, and total road user cost, as well as vehicle operating speeds for different categories of vehicles per kilometer.

In addition to evaluating each component individually, the total road user cost and the average operating speed considering all vehicle types were also calculated to provide a holistic view of the impact. A detailed comparison of various road user cost components was conducted, including fuel cost, lubricating oil, tire wear, spare parts, maintenance labour, vehicle capital cost, crew cost, and overhead charges. Furthermore, both passenger work and non-work time costs were analyzed to understand the broader socio-economic implications of the road interruption.

3.6 Sensitivity Analysis

A sensitivity analysis was also conducted to examine how variations in key parameters influence road user costs and vehicle operating speed. The parameters varied in this analysis included road roughness (ranging from 2 to 9 m/km), road gradient (from 20 to 40 m/km), and horizontal curvature (from 203 to 406 degrees/km).

In addition to geometric and surface characteristics, different traffic volume scenarios were tested to reflect potential reductions in demand due to the disaster. These scenarios considered reductions in Average Annual Daily Traffic (AADT) by -10%, -30%, -50%, and -70%.

3.7 Improvement Scenario Assessment

An improvement scenario was modeled to evaluate the potential benefits of upgrading the 8.53 km gravel detour to a bituminous surface. The upgraded segment was assumed to have an International Roughness Index (IRI) of 5.87 m/km, representing a notable enhancement in surface quality compared to the existing gravel condition.

The objective of this assessment was to estimate the reduction in Road User Costs (RUC) by accounting for expected savings in vehicle operating costs and travel time. This analysis provided insight into the economic viability of the proposed surface improvement by comparing user costs before and after the intervention.

CHAPTER 4: RESULT AND DISCUSSION

4.1. Comparison of Road User Costs per Kilometer for Different Vehicle Categories Before and After disaster.

The vehicle operating cost, travel time cost, and total road user cost per vehicle-kilometer for different categories of vehicles were calculated using the HDM-4 model. The entire 45 km road section was analyzed under both pre-disaster and post-disaster conditions. Following the disaster, the road was divided into two parts: the detoured section (8.53 km) and the unaffected section (37.33 km), which were analyzed separately. Weighted average costs were then calculated to represent the overall 45 km post-disaster condition. Tables 4.1, 4.2, 4.3 and 4.4 present the road user costs per vehicle-kilometer and travel time in minutes /km before the disaster, road user costs and travel time taken for the detoured and unaffected sections and the average road user costs per vehicle-kilometer and average travel time taken in minutes/km after the disaster, respectively

Table:4.1 Vehicle operation cost per veh-km by vehicle before and after disaster.

Vehicle Types	**Before disaster (45 km) (NPR/veh-km)**	**After Disaster**			
		Detoured section (8.53 km)	**Unaffected section (37.33 km)**	**Average (45.86 km) (NPR/veh-km)**	**Percentage Change**
Car	21.04	33.28	20.92	23.22	+10.33
Heavy Truck	114.26	164.94	114.61	123.97	+8.49
Light Truck	53.21	83.29	53.22	58.81	+10.53
Medium Bus	58.03	95.89	58.64	65.57	+12.99
Micro Bus	46.43	72.09	46.16	50.99	+9.81
Small Bus	44.51	74.19	44.75	50.22	+12.82
Motor Cycle	4.06	6.08	4.06	4.43	+9.23
Three-Wheeler	15.01	18.84	15.00	15.71	+4.72
Tractor	27.52	44.35	28.26	31.26	+13.57
Utilities	28.03	43.58	27.86	30.78	+9.81
Jeep	27.93	44.67	27.77	30.92	+10.68

Table 4.1 presents the variation in Vehicle Operating Cost (VOC) per vehicle-kilometer across different vehicle types before and after the disaster along the 45.86 km study section of the BP Highway. The disaster caused a detour of 8.53 km, significantly affecting vehicle costs. For all vehicle categories, the average VOC increased after the disaster. Cars

experienced a rise from NPR 21.04 to NPR 23.22 per veh-km, marking a 10.33% increase. Heavy trucks costs rise from NPR 114.26 to NPR 123.97 per veh-km, an increase of 8.49%. Similarly, light trucks increased from NPR 53.21 to NPR 58.81 per veh-km (+10.53%), while medium buses increased from NPR 58.03 to NPR 65.57 per veh-km (+12.99%). Microbuses and small buses observed increases of 9.81% and 12.82%, respectively. Motorcycles and three-wheelers showed relatively lower increases, with motorcycle VOC rising from NPR 4.06 to NPR 4.43 per veh-km (+9.23%), and three-wheelers from NPR 15.01 to NPR 15.71 (+4.72%). The highest percentage change was observed in tractors, with a 13.57% increase, while utilities and jeeps also experienced notable increases of 9.81% and 10.68%, respectively. These results indicate that disaster-induced detours lead to significant increases in vehicle operating costs across all vehicle types, particularly for medium and heavy vehicles

Table:4.2 Comparison of vehicle travel time before and after disaster.

Vehicle Types	**Before disaster (Minutes/km)**	**After Disaster (Minutes/km)**		
		Detoured section	**Unaffected section**	**Average**
Car	1.75	2.79	1.72	1.85
Heavy Truck	2.58	3.05	2.56	2.64
Light Truck	2.02	2.61	2	2.09
Medium Bus	1.81	2.95	1.78	1.92
Micro Bus	1.69	2.87	1.65	1.80
Small Bus	1.91	2.61	1.89	1.99
Motor Cycle	1.91	2.8	1.88	2.00
Three-Wheeler	2.81	2.92	2.81	2.83
Tractor	2.59	2.84	2.59	2.64
Utilities	1.87	2.91	1.83	1.96
Jeep	1.69	2.78	1.66	1.79

Table 4.2 presents the average travel time required per kilometer by different vehicle types before and after the disaster along the 45.86 km section of the BP Highway. The data show that travel time increased across nearly all vehicle categories following the disaster, primarily due to the 8.53 km detour route. For cars, travel time rose from 1.75 to 1.85 minutes per km, while for heavy trucks, it increased from 2.58 to 2.64 minutes per km. Light trucks experienced an increase from 2.02 to 2.09 minutes per km, and medium buses saw a rise from 1.81 to 1.92 minutes per km. Microbuses and small buses also recorded

increases from 1.69 to 1.80 and 1.91 to 1.99 minutes per km, respectively. Motorcycles experienced a slight increase from 1.91 to 2.00 minutes per km. Utilities and jeeps showed travel time increases from 1.87 to 1.96 and 1.69 to 1.79 minutes per km, respectively. Notably, the travel time for three-wheelers and tractors remained relatively stable, with only marginal increases from 2.81 to 2.83 and 2.59 to 2.64 minutes per km, respectively. These results highlight that while all vehicle types were affected, passenger and light commercial vehicles were more sensitive to the disruption, experiencing relatively higher increases in travel time due to the detour.

Table:4.3 Travel time cost per veh-km by vehicle before and after disaster.

Vehicle Types	Before disaster (45 km) (NPR/veh-km)	After Disaster			
		Detoured section (8.53 km)	Unaffected section (37.33 km)	Average (45.86 km) (NPR/veh-km)	Percentage Change
Car	8.40	12.78	8.26	9.10	+8.33
Heavy Truck	2.07	2.44	2.06	2.13	+2.90
Light Truck	1.66	2.36	1.65	1.78	+7.23
Medium Bus	78.36	119.36	77.19	85.04	+8.52
Micro Bus	16.45	24.25	16.15	17.66	+7.37
Small Bus	51.12	75.29	50.61	55.20	+8.00
Motor Cycle	3.65	5.18	3.61	3.90	+6.72
Three-Wheeler	12.95	13.12	12.93	12.97	+0.13
Tractor	2.14	2.40	2.14	2.19	+2.28
Utilities	7.78	11.20	7.65	8.31	+6.83
Jeep	8.16	12.02	8.01	8.76	+7.31

As shown in table 4.3, there is a noticeable increase across all vehicle types. The total cost increase is particularly evident for public transport vehicles. The medium bus experienced the highest rise, increasing from NPR 78.36 to NPR 85.04 per vehicle-km. Similarly, small buses saw an increase from NPR 51.12 to NPR 55.20, and microbuses from NPR 16.45 to NPR 17.66. Private vehicles, such as cars and jeeps, also experienced a rise, with cars increasing from NPR 8.40 to NPR 9.10 and jeeps from NPR 8.16 to NPR 8.76. The cost for three-wheelers, utilities, and motorcycles also saw slight increases. Heavy truck showed lease increase in travel time cost after disaster.

Table:4.4 Road user cost per veh-km by vehicle before and after disaster.

Vehicle Types	Before disaster (45 km) (NPR/veh-km)	After Disaster			
		Detoured section (8.53 km)	Unaffected section (37.33 km)	Average (45.86 km) (NPR/veh-km)	Percentage Change
Car	29.44	46.06	29.18	32.32	+9.76
Heavy Truck	116.33	167.38	116.67	126.10	+8.40
Light Truck	54.87	85.65	54.87	60.60	+10.44
Medium Bus	136.39	215.25	135.83	150.61	+10.42
Micro Bus	62.88	96.34	62.32	68.64	+9.17
Small Bus	95.63	149.48	95.36	105.43	+10.24
Motor Cycle	7.71	11.26	7.66	8.33	+8.04
Three-Wheeler	27.96	31.97	27.93	28.68	+2.59
Tractor	29.66	46.75	30.41	33.45	+12.75
Utilities	35.81	54.78	35.50	39.09	+9.16
Jeep	36.09	56.69	35.79	39.67	+9.92

As shown in table 4.4, the road user cost per vehicle-km increased across all vehicle categories after the disaster. The tractor faced the highest cost rise, increasing by 12.75% (from NPR 29.66 to NPR 33.45 per vehicle-km). This was followed by light trucks, which saw a 10.53% increase (from NPR 53.21 to NPR 58.81), and medium buses, which rose by 10.42% (from NPR 136.39 to NPR 150.61). Other significantly impacted vehicle types included small buses (+10.24%), cars (+9.76%), microbuses (+9.17%), and utilities (+9.16%). Heavy trucks experienced a 8.40% increase (from NPR 116.33 to NPR 126.10), while jeeps saw an 9.92% rise. Motorcycles and three-wheelers had percentage increases, at 8.04% and 2.59%, respectively. Table 4.3 shows that increase in road user cost is primarily attributed to the detoured section.

4.2.Comparison of Total Annual Road User Costs per Kilometer Considering all Vehicles Before and After the Disaster

The vehicle operating cost (VOC), travel time cost (TTC), and total road user cost (RUC) per vehicle-kilometer for different categories of vehicles were multiplied by their respective traffic volumes and further multiplied by 365 days to estimate the annual VOC, TTC, and RUC per kilometer. The entire 45 km road section was analyzed under both pre-disaster and post-disaster conditions. Following the disaster, the road was divided into two parts: the detoured section (8.53 km) and the unaffected section (37.33 km), which were analyzed separately. Weighted average costs were then calculated to represent the overall 45 km post-disaster condition These values were then aggregated across all vehicle categories to obtain the total annual vehicle operating cost, travel time cost, and road user cost for the road section. Table 4.5, 4.6 and 4.7 present the total annual VOC, TTC and RUC per km before and after disaster respectively.

Table:4.5 Total annual vehicle operation cost per km before and after disaster. (in millions)

Vehicle Types	Before	After Disaster					
		Detoured section	% increase	Unaffected Section	% increase	Average Cost	% increase
Car	13.62	21.54	58.15	13.54	-0.59	15.02	10.28
Heavy Truck	33.53	48.40	44.35	33.63	0.30	36.38	8.50
Light Truck	4.76	7.45	56.51	4.76	0.00	5.26	10.50
Medium Bus	15.57	25.72	65.19	15.73	1.03	17.59	12.97
Micro Bus	15.49	24.05	55.26	15.40	-0.58	17.01	9.81
Small Bus	17.84	29.73	66.65	17.93	0.50	20.13	12.84
Motor Cycle	3.41	5.11	49.85	3.41	0.00	3.73	9.38
Three-Wheeler	0.14	0.18	28.57	0.14	0.00	0.15	7.14
Tractor	0.14	0.23	64.29	0.14	0.00	0.16	14.29
Utilities	6.53	10.15	55.44	6.49	-0.61	7.17	9.80
Jeep	7.76	12.41	59.92	7.71	-0.64	8.59	10.70
Total	**118.79**	**184.97**	**55.71**	**118.88**	**0.08**	**131.18**	**10.43**

Table 4.5 presents the total annual Vehicle Operating Cost (VOC) per kilometer by vehicle type before and after the disaster, expressed in millions of NPR. The data reveal a substantial increase in VOC across all vehicle categories, particularly within the 8.53 km detoured section, while the unaffected 37.33 km section showed minimal or no increase. The annual VOC for cars increased from NPR 13.62 million/km to NPR 21.54 million/km in the detoured section, a 58.15% increase, whereas the unaffected section saw a slight decline of 0.59%. Heavy trucks experienced a 44.35% increase with VOC rising from NPR 33.53 million/km to NPR 48.40 million/km in the detoured section. Similarly, significant increases were observed for light trucks (56.51%), medium buses (65.19%), and small buses (66.65%). Tractors registered the highest percentage increase at 64.29%. In contrast, the unaffected section showed negligible variations.

In total, the annual VOC for the detoured section increased from NPR 118.79 million/km before the disaster to NPR 184.97 million/km after the disaster, marking a 55.71% rise. In comparison, the average annual VOC across the entire 45.86 km stretch increased to NPR 131.18 million/km, representing a 10.44% overall increase.

Table:4.6 Total annual travel time cost per km before and after disaster. (in millions)

Vehicle Types	**Before**	**After Disaster**					
		Detoured section	**% increase**	**Unaffected Section**	**% increase**	**Average Cost**	**% increase**
Car	5.44	8.27	52.02	5.34	-1.84	5.89	8.27
Heavy Truck	0.61	0.72	18.03	0.60	-1.64	0.63	3.28
Light Truck	0.15	0.21	40.00	0.15	0.00	0.16	6.67
Medium Bus	21.02	32.02	52.33	20.71	-1.47	22.81	8.52
Micro Bus	5.49	8.09	47.36	5.39	-1.82	5.89	7.29
Small Bus	20.49	30.18	47.29	20.28	-1.02	22.12	7.96
Motor Cycle	3.07	4.35	41.69	3.03	-1.30	3.28	6.84
Three-Wheeler	0.12	0.12	0.00	0.12	0.00	0.12	0.00
Tractor	0.01	0.01	0.00	0.01	0.00	0.01	0.00
Utilities	1.81	2.61	44.20	1.78	-1.66	1.93	6.63
Jeep	2.27	3.34	47.14	2.23	-1.76	2.43	7.05
Total	**60.48**	**89.92**	**48.68**	**59.64**	**-1.39**	**65.27**	**7.92**

Table 4.6 shows the total annual travel time cost (TTC) per kilometer by vehicle type before and after the disaster, expressed in millions of NPR. Overall, TTC in the detoured section increased significantly from 60.47 million to 89.92 million NPR/km, representing an approximate 48.68 % rise. In contrast, the unaffected section is slightly decreased by 1.39%. When averaged over the entire 45 km road section, the total TTC increased from 60.48 million to 65.27 million NPR/km with an overall rise of 7.92 %

Table:4.7 Total annual road user cost per km before and after disaster. (in millions)

Vehicle Types	**Before**	**After Disaster**					
		Detoured section	**% increase**	**Unaffected Section**	**% increase**	**Average Cost**	**% increase**
Car	19.06	29.81	56.40	18.88	-0.94	20.91	9.71
Heavy Truck	34.14	49.12	43.88	34.23	0.26	37.01	8.41
Light Truck	4.91	7.66	56.01	4.91	0.00	5.42	10.39
Medium Bus	36.59	57.74	57.80	36.44	-0.41	40.40	10.41
Micro Bus	20.98	32.14	53.19	20.79	-0.91	22.90	9.15
Small Bus	38.33	59.91	56.30	38.21	-0.31	42.25	10.23
Motor Cycle	6.48	9.46	45.99	6.44	-0.62	7.01	8.18
Three-Wheeler	0.26	0.30	15.38	0.26	0.00	0.27	3.85
Tractor	0.15	0.24	60.00	0.15	0.00	0.17	13.33
Utilities	8.34	12.76	53.00	8.27	-0.84	9.10	9.11
Jeep	10.03	15.75	57.03	9.94	-0.90	11.02	9.87
Total	**179.27**	**274.89**	**53.34**	**178.52**	**-0.42**	**196.46**	**9.59**

Table 4.7 presents the total annual Road User Cost (RUC) per kilometer (in millions of NPR) for various vehicle types before and after the disaster. The detoured section showed a significant rise in RUC, with cars increasing from 19.06 to 29.81 million NPR/km (a 56.40% rise), heavy trucks from 34.14 to 49.12 million NPR/km (43.88%), and medium buses from 36.59 to 57.74 million NPR/km (57.80%). Likewise, light trucks, micro buses, small buses, motorcycles, utilities, and jeeps experienced increases between 45% and 59%, while three-wheelers and tractors saw more moderate increases of 15.38% and 60.00%, respectively. On the other hand, the unaffected section showed negligible variations.

In total, the annual RUC for the detoured section increased from NPR 179.27 million/km before the disaster to NPR 274.89 million/km after the disaster, marking a 53.34% rise. In comparison, the average annual VOC across the entire 45 km stretch increased to NPR 196.46 million/km, representing a 9.59 % overall increase.

4.3. Analysis of different Road User Component

The Highway Development and Management (HDM-4) model evaluates various components of Road User Cost (RUC), including fuel cost, lubricating oil, tyres, spare parts, maintenance labor, vehicle capital cost, crew wages, overhead costs, and passenger-related costs (work and non-work time). These components constitute a significant portion of the total cost borne by road users and are directly influenced by factors such as road surface condition, traffic flow, and disruptions caused by disasters or structural damage. This study assessed the variation in each RUC component before and after the disaster. The entire 45 km road section was analyzed under both pre-disaster and post-disaster conditions. The range of road user cost component values per vehicle-kilometer for different vehicle types is illustrated in Figures 4.1 through 4.11.

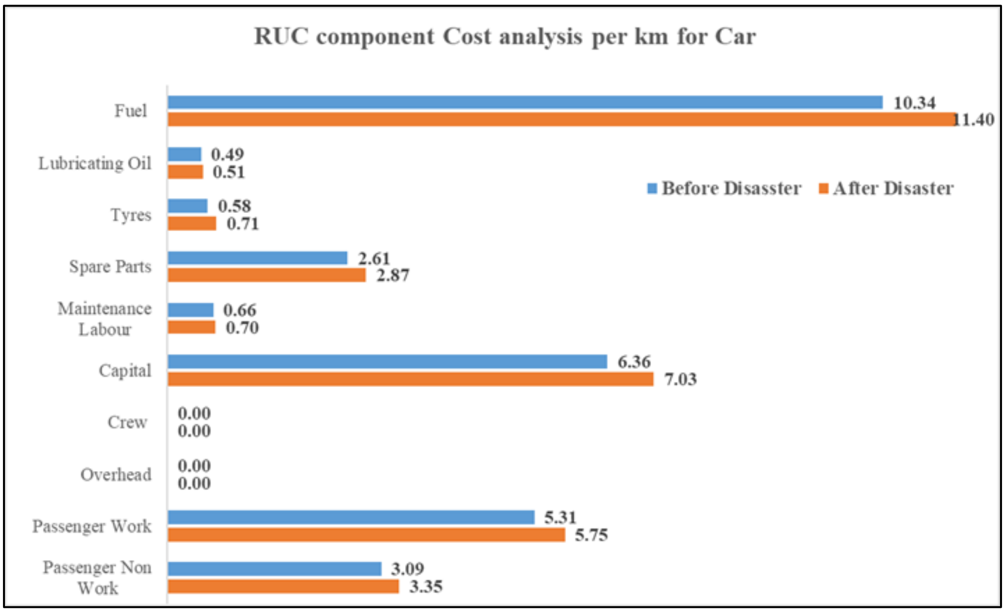

Figure 4.1: Road user component cost analysis per km for car.

Figure 4.1 illustrates the increase in road user cost components for cars following the disaster. The most significant rise is observed in fuel costs, which increased from NPR 10.34 to NPR 11.40 per vehicle-kilometer. Additional notable increases include capital costs (from NPR 6.36 to NPR 7.03), passenger work time costs (from NPR 5.31 to NPR 5.75), and tyre costs (from NPR 0.58 to NPR 0.71).

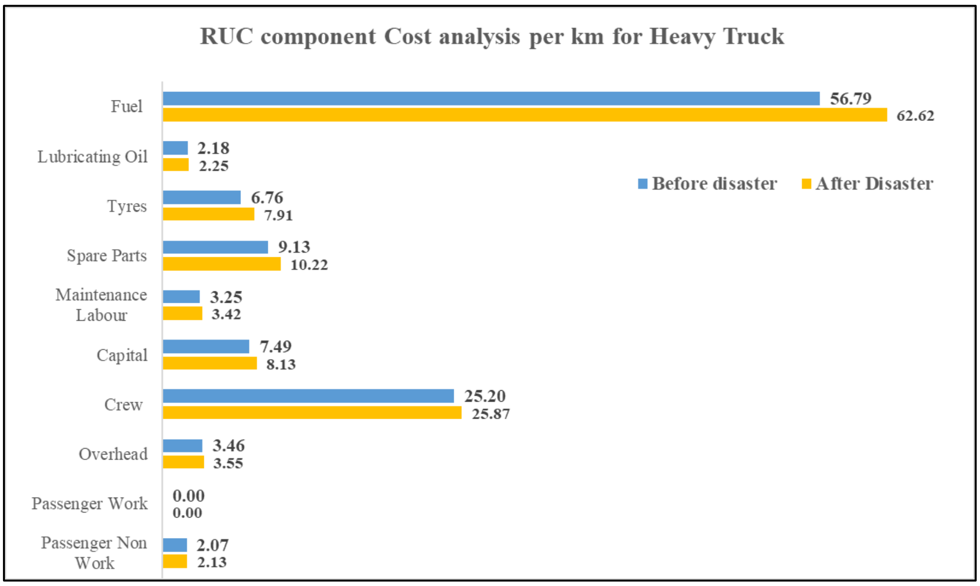

Figure 4.2: Road user component cost analysis per km for Heavy Truck.

Figure 4.2 illustrates the increase in road user cost components for heavy trucks following the disaster. The most significant rise is observed in fuel costs, which increased from NPR 56.79 to NPR 62.62 per vehicle-kilometer. Additional notable increases include tyre costs (from NPR 6.76 to NPR 7.91), spare parts costs (from NPR 9.13 to NPR 10.22), and capital costs (from NPR 7.49 to NPR 8.13).

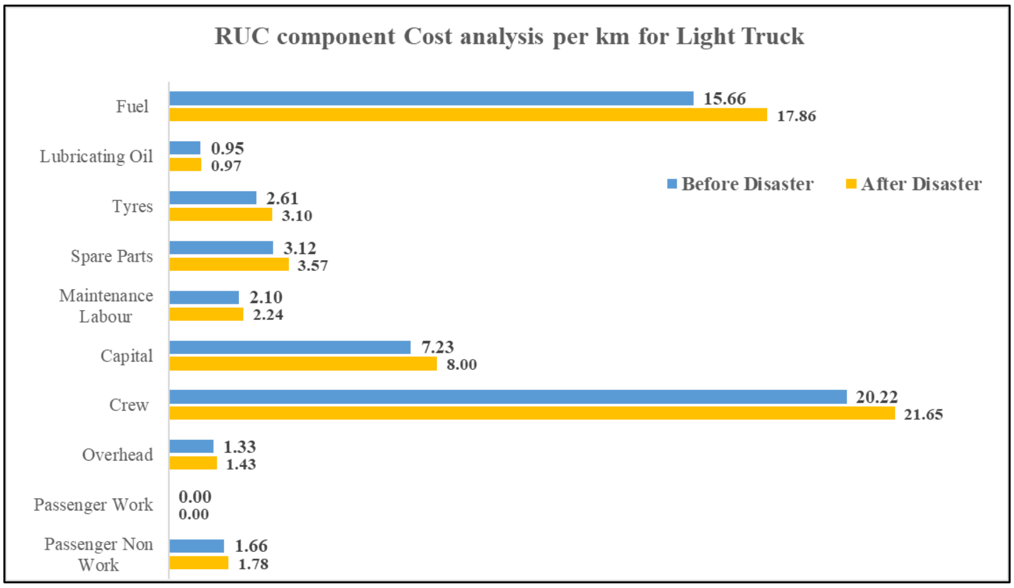

Figure 4.3: Road user component cost analysis per km for Light Truck

Fig 4.3 illustrates the increase in road user cost components for light trucks following the disaster. The most significant rise is observed in fuel costs, which increased from NPR 15.66 to NPR 17.86 per vehicle-kilometer. Additional notable increases include crew costs (from NPR 20.22 to NPR 21.65), capital costs (from NPR 7.23 to NPR 8.00), and tyre costs (from NPR 2.61 to NPR 3.10).

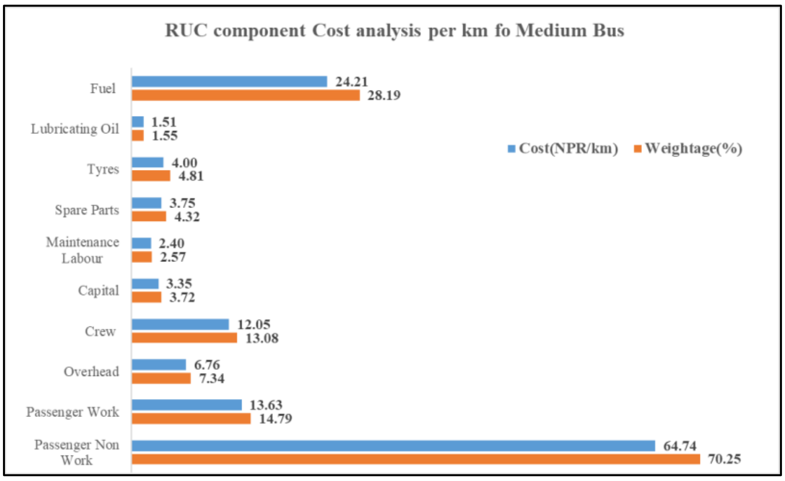

Figure 4.4: Road user component cost analysis per km for Medium Bus

Figure 4.4 illustrates the increase in road user cost components for medium buses following the disaster. The most significant rise is observed in passenger non-work time costs, which increased from NPR 64.74 to NPR 70.25 per vehicle-kilometer. Additional notable increases include fuel costs (from NPR 24.21 to NPR 28.19), crew costs (from NPR 12.05 to NPR 13.08), and passenger work time costs (from NPR 13.63 to NPR 14.79).

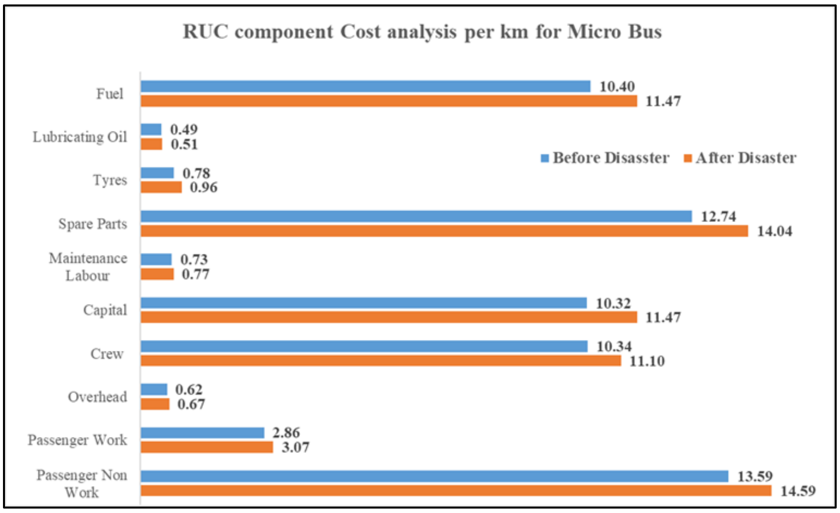

Figure 4.5: Road user component cost analysis per km for Micro Bus

Figure 4.5 illustrates the increase in road user cost components for micro buses following the disaster. The most significant rise is observed in spare parts costs, which increased from NPR 12.74 to NPR 14.04 per vehicle-kilometer. Additional notable increases include fuel costs (from NPR 10.40 to NPR 11.47), capital costs (from NPR 10.32 to NPR 11.47), and crew costs (from NPR 10.34 to NPR 11.10). Furthermore, passenger non-work time costs increased from NPR 13.59 to NPR 14.59.

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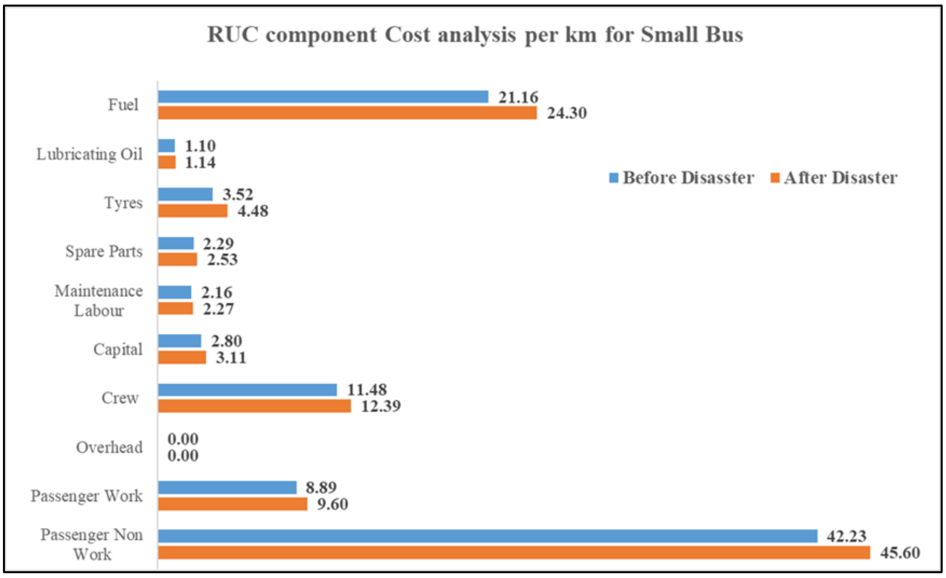

Figure 4.6: Road user component cost analysis per km for Small Bus

Figure 4.6 illustrates the increase in road user cost components for small buses following the disaster. The most significant rise is observed in fuel costs, which increased from NPR 21.16 to NPR 24.30 per vehicle-kilometer. Additional notable increases include tyre costs (from NPR 3.52 to NPR 4.48), capital costs (from NPR 2.80 to NPR 3.11), and crew costs (from NPR 11.48 to NPR 12.39). Furthermore, passenger non-work time costs increased from NPR 42.23 to NPR 45.60..

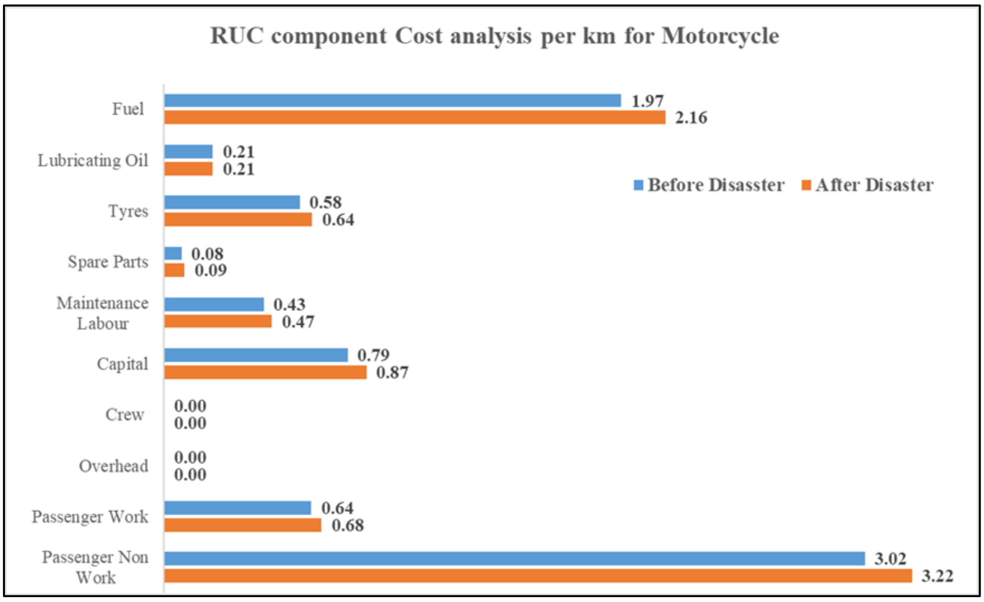

Figure 4.7: Road user component cost analysis per km for Motorcycle

Figure 4.7 illustrates the increase in road user cost components for motorcycles following the disaster. The most significant rise is observed in fuel costs, which increased from NPR 1.97 to NPR 2.16 per vehicle-kilometer. Additional notable increases include tyre costs (from NPR 0.58 to NPR 0.64) and capital costs (from NPR 0.79 to NPR 0.87). Furthermore, passenger non-work time costs increased from NPR 3.02 to NPR 3.22.

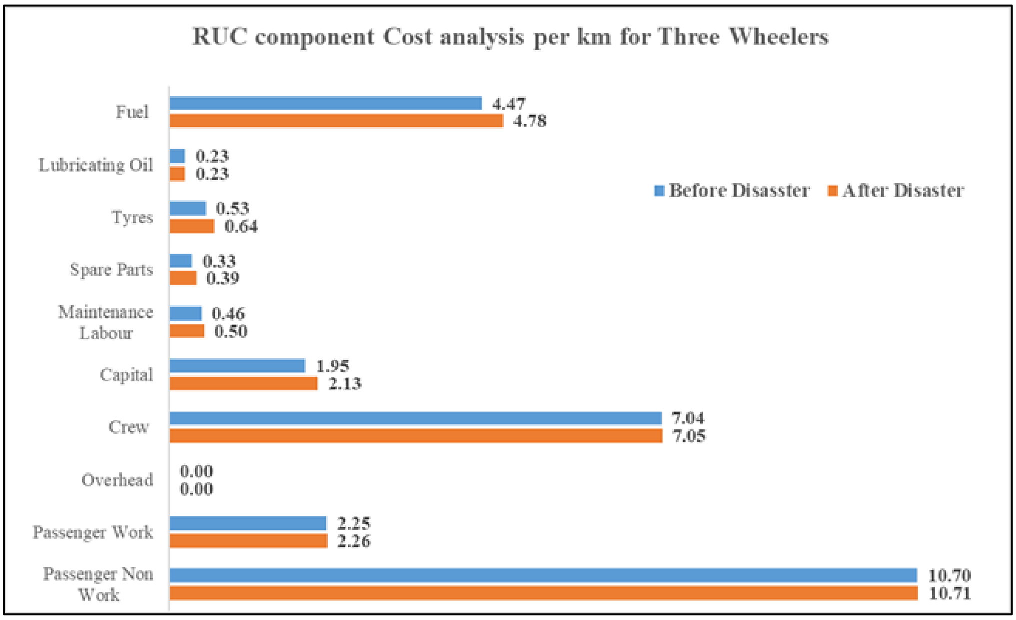

Figure 4.8: Road user component cost analysis per km for Three wheelers

Figure 4.8 illustrates the increase in road user cost components for three-wheelers following the disaster. The most significant rise is observed in fuel costs, which increased from NPR 4.47 to NPR 4.78 per vehicle-kilometer. Additional notable increases include tyre costs (from NPR 0.53 to NPR 0.64), spare parts costs (from NPR 0.33 to NPR 0.39), and maintenance labor costs (from NPR 0.46 to NPR 0.50). Furthermore, capital costs increased from NPR 1.95 to NPR 2.13, while crew costs slightly rose from NPR 7.04 to NPR 7.05.

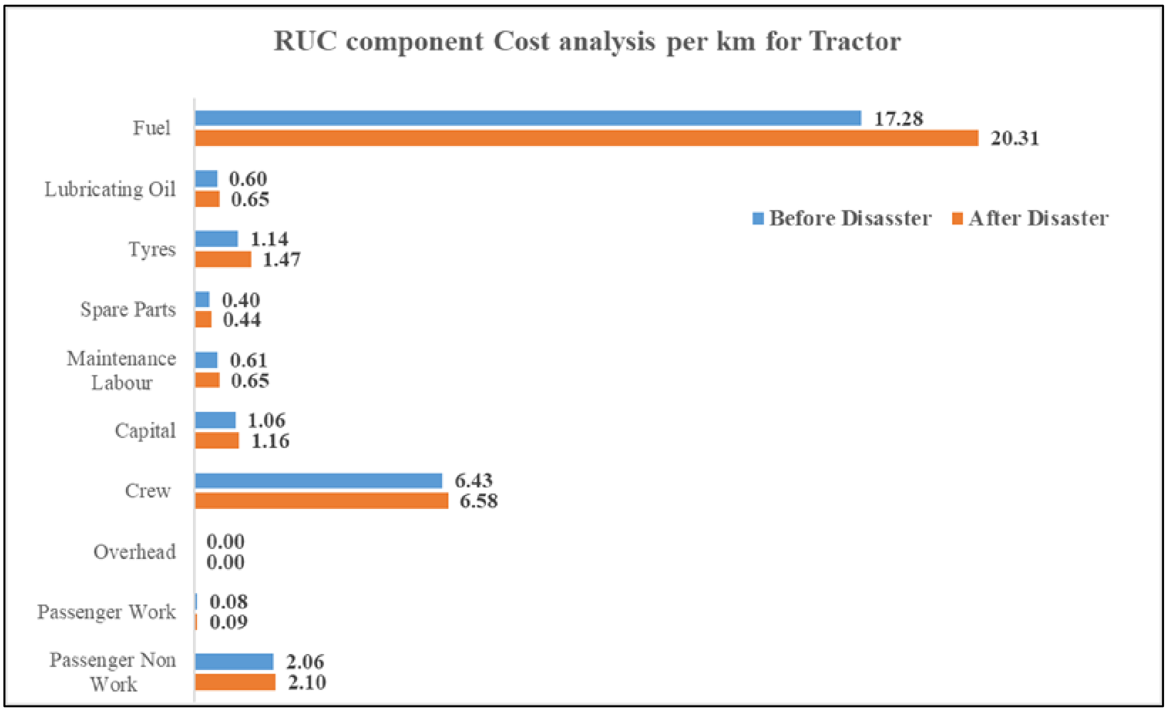

Figure 4.9: Road user component cost analysis per km for Tractor .

Figure 4.9 presents the increase in road user cost components for tractors following the disaster. The most significant increase is observed in fuel costs, which rose from NPR 17.28 to NPR 20.31 per vehicle-kilometer. Additionally, there was a rise in tyre costs (from NPR 1.14 to NPR 1.47), lubricating oil costs (from NPR 0.60 to NPR 0.65), spare parts costs (from NPR 0.40 to NPR 0.44), and maintenance labor costs (from NPR 0.61 to NPR 0.65).

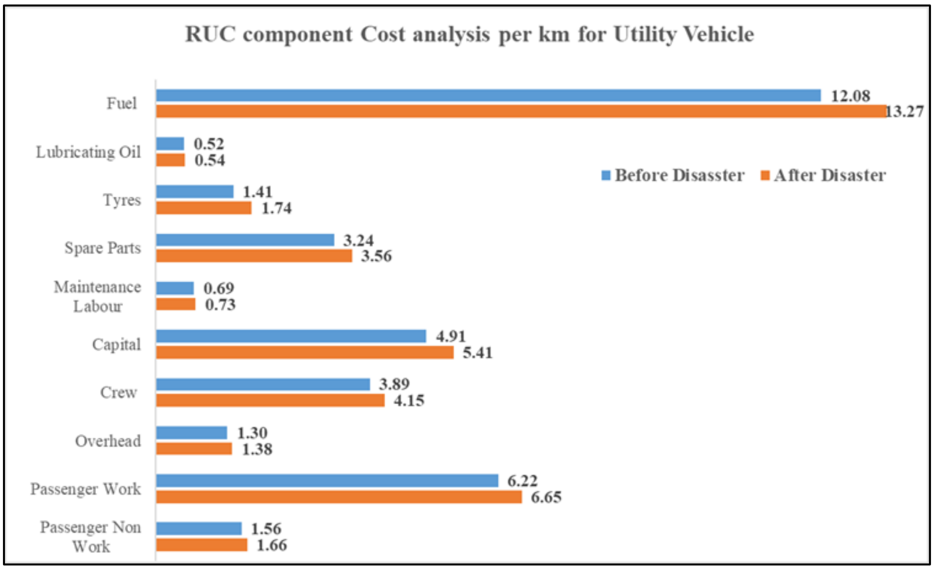

Figure 4.10: Road user component cost analysis per km for Utility vehicle

Figure 4.10 illustrates the impact of road disruptions on road user cost components for utility vehicles. The most significant increase is seen in fuel costs, which rose from NPR 12.08 to NPR 13.27 per vehicle-kilometer. Similarly, tyre costs increased from NPR 1.41 to NPR 1.74, while spare parts costs rose from NPR 3.24 to NPR 3.56. Additionally, capital costs increased from NPR 4.91 to NPR 5.41, and crew costs rose from NPR 3.89 to NPR 4.15. The rise in maintenance labor costs (from NPR 0.69 to NPR 0.73) and overhead costs (from NPR 1.30 to NPR 1.38)

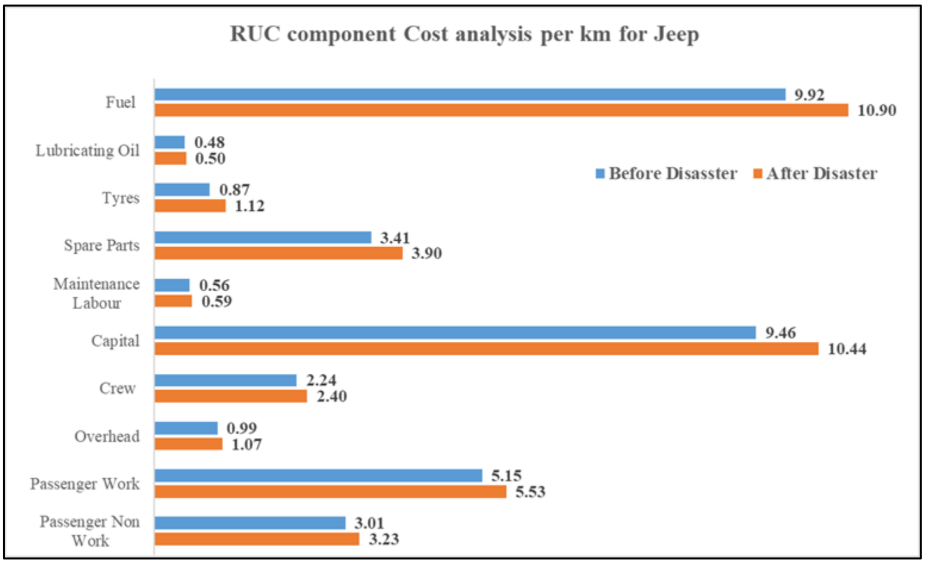

Figure 4.11: Road user component cost analysis per km for Jeep

Figure 4.11 presents the impact of road disruptions on road user cost components for jeeps. The most significant increase is observed in fuel costs, which rose from NPR 9.92 to NPR 10.90 per vehicle-kilometer. Similarly, tyre costs increased from NPR 0.87 to NPR 1.12, while spare parts costs rose from NPR 3.41 to NPR 3.90. Additionally, capital costs increased from NPR 9.46 to NPR 10.44, and crew costs rose from NPR 2.24 to NPR 2.40. Maintenance labor costs also increased slightly, from NPR 0.56 to NPR 0.59, along with a rise in overhead costs from NPR 0.99 to NPR 1.07.

4.3.1 Analysis of Fuel Cost Before and After Disaster

From figure 4.1 to 4.11, it is evident that fuel cost alone constitutes of about 30 percent of all road user component. Fuel cost is found to be the dominant component among all road user cost components. The total annual fuel cost per km, considering all vehicle categories, was calculated by multiplying the fuel cost per kilometer for each vehicle category by their respective traffic volumes, and further multiplying by 365 days. The entire 45 km road section was analyzed under both pre-disaster and post-disaster conditions. Following the disaster, the road was divided into two parts: the detoured section (8.53 km) and the unaffected section (37.33 km), which were analyzed separately. Weighted average costs were then calculated to represent the overall 45 km post-disaster condition. The annual fuel costs before and after the disaster are presented in Table 4.8.

Table:4.8 Total annual fuel cost per km. (in millions)

Before Disaster	After Disaster					
	Detoured section	**% increase**	**Unaffected Section**	**% increase**	**Average Cost**	**% increase**
50.56	81.72	61.62	50.82	0.51	56.56	11.87

Table 4.8 presents the total annual fuel cost per kilometer (in millions of NPR) before and after the disaster. The detoured section experienced a substantial increase in fuel cost, rising from 50.56 to 81.72 million NPR/km, which corresponds to a 61.62% increase. In contrast, the unaffected section recorded a marginal increase of 0.51%, with costs rising slightly from 50.56 to 50.82 million NPR/km. When averaged over the entire 45 km road section, the fuel cost increased to 56.56 million NPR/km, marking an overall increase of 11.87%.

This highlights the significant impact of detours on vehicle fuel consumption, contributing notably to the overall rise in road user costs.

4.4 Average Operating Speed of Vehicles Before and After Disaster

The average operating speed of each vehicle category was calculated using the HDM-4 model for both before and after the disaster, and the results are presented in Table 4.9.

Table:4.9 Average operating speed of vehicles before and after disaster.

Vehicles	Before Disaster (kmph)	After disaster(kmph)		
		Detoured section	Unaffected section	Average
Car	34.27	21.53	34.97	32.47
Heavy Truck	23.28	19.64	23.48	22.77
Light Truck	29.74	23.03	30.02	28.72
Medium Bus	33.19	20.36	33.78	31.28
Micro Bus	35.51	20.87	36.29	33.42
Small Bus	31.40	23.02	31.76	30.13
Motor Cycle	31.40	21.44	31.87	29.93
Three Wheeler	21.35	20.55	21.38	21.23
Tractor	23.15	21.11	23.14	22.76
Utilities	32.17	20.62	32.81	30.54
Jeep	35.46	21.55	36.25	33.52

Table 4.9 shows that each vehicle's average operating speed has reduced after the disaster. The average speed of cars decreased from 34.27 km/h before the disaster to 32.47 km/h after, with the detoured section recording a much lower speed of 21.53 km/h. Heavy trucks showed a reduction from 23.28 km/h to 22.77 km/h, and medium buses dropped from 33.19 km/h to 31.28 km/h. Similar declines were recorded for microbuses (35.51 km/h to 33.42 km/h), utilities (32.17 km/h to 30.54 km/h), and jeeps (35.46 km/h to 33.52 km/h). The detoured segments consistently exhibited lower speeds compared to unaffected sections, confirming the operational delays caused by road damage

4.5 Sensitivity Analysis

Sensitivity analysis was conducted to access how variations in traffic volume, IRI, rise/fall per km and road curvature affect the road user cost and operating speeds.

4.5.1 Road User Cost Sensitivity to Roughness, Gradient and Curvature.

The International Roughness Index (IRI) of the road section was varied from 2 m/km to 9 m/km in increments of 1 m/km while maintaining a constant traffic volume. Similarly, road gradient and horizontal curvature values were also varied over their respective ranges using the same approach. Following this initial variation, the traffic volume was decreased by 10%, and the IRI, gradient, and curvature were once again varied across the same range. This process was repeated iteratively to evaluate the sensitivity of road user costs to these key parameters. Table 4.10 presents the traffic volume scenarios used for the sensitivity analysis

Table 4.10: Traffic volume Scenario for sensitive analysis.

Vehicle Types	**AADT**	**-10%**	**-30%**	**-50%**	**-70%**
Car	1773	1596	1241	887	532
Heavy Truck	804	724	563	402	241
Jeep	761	685	533	381	228
Light Truck	245	221	172	123	74
Medium Bus	735	662	515	368	221
Micro Bus	914	823	640	457	274
Motor Cycle	2303	2073	1612	1152	691
Small Bus	1098	988	769	549	329
Three-Wheeler	26	23	18	13	8
Tractor	14	13	10	7	4
Utilities	638	574	447	319	191
Total	**9311**	**8382**	**6520**	**4658**	**2793**

As shown in Table 4.10, the baseline traffic volume prior to the disaster was 9,311 AADT. Following the disaster, observed traffic volume dropped significantly to approximately 3,000 AADT due to extensive road damage and associated disruptions. While this reduction suggests a decline in road usage, it is important to consider that a portion of the traffic may have rerouted via alternative corridors rather than being eliminated entirely. Thus, the post-disaster drop in observed volume likely reflects diversion rather than an absolute decline in travel demand.

To realistically simulate this scenario within the HDM-4 model and assess the sensitivity of Road User Costs (RUC) under varying traffic conditions, multiple reduced traffic volume cases were modeled. These included traffic reductions of 10%, 30%, 50%, and 70% from the baseline AADT. This approach allows for evaluating the economic impact under different levels of diversion and helps capture the broader implications of disaster-induced network disruption.

4.5.1.1 Road User Cost Sensitivity to Roughness

The traffic volume (AADT) was set at 9,311 PCU, and the International Roughness Index (IRI) of the road section was varied from 2 m/km to 9 m/km in increments of 1 m/km. For each IRI value, the corresponding road user cost (RUC), vehicle operating cost (VOC), travel time cost (TTC), and average vehicle operating speeds were calculated and recorded. Tables 4.11 to 4.30 present the variations in VOC, TTC, RUC, and operating speeds with respect to IRI under different traffic volume scenarios, ranging from 0% to a 70 % reduction in AADT. The notations used for each vehicle are C=car, HT=Heavy Truck, LT= Light Truck, MB=Medium Bus, MiB=Micro Bus, SB=Small Bus, MC=Motor Cycle, TW=Three Wheelers, T=Tractor, U= Utilities, J=Jeep.

Table:4.11 Vehicle operation cost sensitivity to roughness. at traffic volume (AADT) 9311 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	18.92	101.69	47.35	52.29	40.93	40.35	3.72	14.00	26.23	25.34	24.91
3	19.17	104.09	48.26	53.18	41.41	41.07	3.76	14.15	26.46	25.73	25.21
4	19.72	107.55	49.82	54.83	42.99	42.19	3.85	14.40	26.79	26.45	26.00
5	20.41	111.23	51.63	56.61	44.82	43.44	3.96	14.70	27.16	27.30	27.00
6	21.22	115.07	53.67	58.51	46.85	44.83	4.08	15.07	27.60	28.27	28.19
7	22.11	119.00	55.85	60.49	48.98	46.32	4.21	15.44	28.10	29.31	29.46
8	23.06	122.87	58.12	62.47	51.19	47.89	4.35	15.80	28.63	30.40	30.80
9	24.02	126.38	60.35	64.55	53.42	49.43	4.47	16.15	29.13	31.49	32.13

Table 4.12 presents the variation in travel time cost (TTC) per vehicle-kilometer across different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a constant traffic volume of 9,311 PCU. For cars, TTC increases from NPR 7.55 to 9.62, and for medium buses, it rises from NPR 70.94 to 88.77. Microbuses show an increase from NPR 15.16 to 18.43, small buses from NPR 46.25 to 57.93, and motorcycles from NPR 3.38 to 4.09. Three-wheelers increase from NPR 12.39 to 13.49, tractors from NPR 2.09 to 2.21, utilities from NPR 7.10 to 8.70, and jeeps from NPR 7.53 to 9.14.

Table:4.12: Travel time cost sensitivity to roughness at traffic volume (AADT) 9311 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	7.55	1.86	1.50	70.94	15.16	46.25	3.38	12.39	2.09	7.10	7.53
3	7.71	1.91	1.53	72.51	15.40	47.21	3.43	12.50	2.10	7.25	7.64
4	7.93	1.97	1.58	74.45	15.74	48.46	3.50	12.65	2.11	7.43	7.81
5	8.21	2.03	1.63	76.71	16.17	49.96	3.59	12.81	2.13	7.63	8.02
6	8.50	2.09	1.68	79.32	16.65	51.70	3.69	12.99	2.15	7.87	8.26
7	8.84	2.16	1.74	82.23	17.18	53.62	3.81	13.17	2.17	8.13	8.52
8	9.22	2.23	1.81	85.39	17.78	55.71	3.94	13.32	2.19	8.40	8.82
9	9.62	2.29	1.88	88.77	18.43	57.93	4.09	13.49	2.21	8.70	9.14

Table 4.13 presents the variation in road user cost (RUC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a constant traffic volume of 9,311 PCU. For cars, the RUC rises from NPR 26.47 to 33.64, while heavy trucks show an increase from NPR 103.55 to 128.67, and light trucks from NPR 48.85 to 62.23. The RUC for medium buses increases from NPR 123.23 to 153.32, microbuses from NPR 56.09 to 71.85, and small buses from NPR 86.60 to 107.36. Motorcycles show an increase from NPR 7.10 to 8.56, three-wheelers from NPR 26.38 to 29.64, and tractors from NPR 28.31 to 31.34. For utilities, RUC rises from NPR 32.44 to 40.19, and for jeeps, from NPR 32.44 to 41.27

Table:4.13: Road user cost sensitivity to roughness at traffic volume (AADT) 9311 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	26.47	103.55	48.85	123.23	56.09	86.60	7.10	26.38	28.31	32.44	32.44
3	26.88	106.00	49.79	125.69	56.81	88.28	7.19	26.65	28.56	32.98	32.85
4	27.66	109.52	51.40	129.28	58.73	90.64	7.35	27.04	28.90	33.88	33.81
5	28.62	113.26	53.26	133.32	60.99	93.41	7.54	27.51	29.29	34.93	35.02
6	29.72	117.16	55.35	137.82	63.49	96.53	7.77	28.06	29.74	36.14	36.45
7	30.96	121.16	57.59	142.72	66.16	99.94	8.02	28.61	30.27	37.44	37.99
8	32.28	125.10	59.93	147.87	68.97	103.60	8.29	29.13	30.82	38.81	39.62
9	33.64	128.67	62.23	153.32	71.85	107.36	8.56	29.64	31.34	40.19	41.27

Table 4.14 presents the variation in average operating speed (in km/h) for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a constant traffic volume of 9,311 PCU. For cars, the operating speed decreases from 38.51 km/h to 29.41 km/h, while heavy trucks drop from 26.22 km/h to 20.99 km/h, and light trucks from 33.47 km/h to 26.04 km/h. The speed of medium buses reduces from 37.09 km/h to 28.86 km/h, microbuses from 38.75 km/h to 31.21 km/h, and small buses from 35.14 km/h to 27.35 km/h. Motorcycles experience a decrease from 34.25 km/h to 27.71 km/h, three-wheelers from 22.34 km/h to 20.47 km/h, and tractors from 23.77 km/h to 22.39 km/h. For utility vehicles, speed declines from 35.61 km/h to 28.41 km/h, while for jeeps, it drops from 38.68 km/h to 31.19 km/h.

Table:4.14 Average operating speed sensitivity to roughness at traffic volume (AADT) 9311 pcu(Kmph)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	38.51	26.22	33.47	37.09	38.75	35.14	34.25	22.34	23.77	35.61	38.68
3	37.66	25.43	32.62	36.23	38.11	34.34	33.70	22.12	23.64	34.81	38.04
4	36.53	24.64	31.61	35.17	37.24	33.34	32.96	21.87	23.49	33.88	37.18
5	35.20	23.85	30.52	33.99	36.18	32.21	32.07	21.58	23.30	32.84	36.13
6	33.79	33.79	33.79	33.79	33.79	33.79	33.79	33.79	33.79	33.79	33.79
7	32.32	22.31	28.24	31.43	33.78	29.77	29.96	20.99	22.87	30.62	33.74
8	30.84	21.58	27.12	30.13	32.50	28.54	28.84	20.73	22.64	29.51	32.47
9	29.41	20.99	26.04	28.86	31.21	27.35	27.71	20.47	22.39	28.41	31.19

Table 4.15 presents the variation in vehicle operation cost (VOC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 8,382 PCU (-10% of the base volume). For cars, the VOC rises from NPR 18.53 to 23.72, while heavy trucks show an increase from NPR 100.55 to 125.95, and light trucks from NPR 46.44 to 59.55. The VOC for medium buses increases from NPR 51.06 to 63.60, microbuses from NPR 40.15 to 52.79, and small buses from NPR 39.61 to 48.79. Motorcycles show an increase from NPR 3.69 to 4.44, three-wheelers from NPR 13.92 to 16.11, and tractors from NPR 26.12 to 28.99. For utility vehicles, VOC rises from NPR 24.77 to 31.05, and for jeeps, from NPR 24.39 to 31.70.

Table:4.15 Vehicle operation cost sensitivity to roughness at -10% traffic volume (AADT) 8382 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	18.53	100.55	46.44	51.06	40.15	39.61	3.69	13.92	26.12	24.77	24.39
3	18.78	103.01	47.41	51.94	40.61	40.36	3.73	14.07	26.35	25.17	24.67
4	19.32	106.70	49.04	53.62	42.17	41.52	3.82	14.32	26.67	25.92	25.46
5	20.00	110.41	50.84	55.47	43.98	42.82	3.92	14.62	27.04	26.80	26.44
6	20.84	114.27	52.88	57.46	46.03	44.23	4.05	14.98	27.46	27.81	27.64
7	21.77	118.21	55.04	59.54	48.22	45.71	4.18	15.38	27.97	28.90	28.95
8	22.76	122.09	57.30	61.55	50.49	47.26	4.31	15.76	28.49	29.98	30.32
9	23.72	125.95	59.55	63.60	52.79	48.79	4.44	16.11	28.99	31.05	31.70

Table 4.16 presents the variation in travel time cost (TTC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 8,382 PCU (-10% of the base volume). For cars, the TTC rises from NPR 7.22 to 9.38. The TTC for medium buses increases from NPR 67.93 to 86.57, microbuses from NPR 14.49 to 17.92, and small buses from NPR 44.51 to 56.58. Motorcycles show an increase from NPR 3.25 to 4.00, three-wheelers from NPR 12.30 to 13.44, and tractors from NPR 2.07 to 2.20. For utility vehicles, TTC rises from NPR 6.82 to 8.49, and for jeeps, from NPR 7.19 to 8.89.

Table:4.16: Travel time cost sensitivity to roughness at -10% traffic volume (AADT) 8382 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	7.22	1.83	1.45	67.93	14.49	44.51	3.25	12.30	2.07	6.82	7.19
3	7.38	1.88	1.49	69.46	14.72	45.55	3.31	12.41	2.08	6.97	7.31
4	7.59	1.94	1.54	71.49	15.05	46.92	3.38	12.55	2.09	7.16	7.47
5	7.87	2.01	1.59	73.96	15.47	48.56	3.48	12.71	2.11	7.39	7.68
6	8.20	2.07	1.64	76.81	15.98	50.37	3.59	12.90	2.13	7.64	7.93
7	8.57	2.14	1.70	79.98	16.56	52.28	3.72	13.09	2.15	7.92	8.22
8	8.98	2.21	1.77	83.21	17.21	54.36	3.85	13.28	2.17	8.20	8.54
9	9.38	2.28	1.84	86.57	17.92	56.58	4.00	13.44	2.20	8.49	8.89

Table 4.17 presents the variation in road user cost (RUC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 8,382 PCU (-10% of the base volume). For cars, the RUC rises from NPR 25.76 to 33.10, while heavy trucks show an increase from NPR 102.38 to 128.23, and light trucks from NPR 47.89 to 61.39. The RUC for medium buses increases from NPR 118.99 to 150.17, microbuses from NPR 54.64 to 70.71, and small buses from NPR 84.12 to 105.37. Motorcycles show an increase from NPR 6.94 to 8.43, three-wheelers from NPR 26.22 to 29.55, and tractors from NPR 28.19 to 31.18. For utility vehicles, RUC rises from NPR 31.59 to 39.54, and for jeeps, from NPR 31.58 to 40.59.

Table:4.17 Road user cost sensitivity to roughness at -10% traffic volume (AADT) 8382 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	25.76	102.38	47.89	118.99	54.64	84.12	6.94	26.22	28.19	31.59	31.58
3	26.15	104.89	48.90	121.40	55.33	85.91	7.04	26.48	28.43	32.14	31.98
4	26.91	108.64	50.58	125.11	57.22	88.43	7.20	26.87	28.76	33.08	32.93
5	27.87	112.42	52.43	129.43	59.45	91.38	7.40	27.34	29.15	34.19	34.12
6	29.04	116.34	54.52	134.27	62.01	94.60	7.64	27.88	29.59	35.46	35.57
7	30.34	120.35	56.74	139.53	64.78	97.99	7.90	28.47	30.12	36.82	37.17
8	31.73	124.30	59.07	144.76	67.70	101.63	8.16	29.03	30.66	38.17	38.86
9	33.10	128.23	61.39	150.17	70.71	105.37	8.43	29.55	31.18	39.54	40.59

Table 4.18 presents the variation in average vehicle operating speed (km/h) for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 8,382 PCU (-10% of the base volume). For cars, the operating speed declines from 39.73 km/h to 30.05 km/h, while heavy trucks experience a reduction from 26.65 km/h to 21.09 km/h, and light trucks from 34.33 km/h to 26.55 km/h. The operating speed for medium buses decreases from 38.24 km/h to 29.49 km/h, microbuses from 39.99 km/h to 31.95 km/h, and small buses from 36.15 km/h to 27.91 km/h. Motorcycles show a decline from 35.22 km/h to 28.28 km/h, three-wheelers from 22.50 km/h to 20.54 km/h, and tractors from 23.94 km/h to 22.56 km/h. For utility vehicles, the speed decreases from 36.68 km/h to 29.01 km/h, and for jeeps, from 39.91 km/h to 31.92 km/h.

Table:4.18 Average vehicle operating speed sensitivity to roughness at -10% traffic volume (AADT) 8382 pcu(Kmph)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	39.73	26.65	34.33	38.24	39.99	36.15	35.22	22.50	23.94	36.68	39.91
3	38.85	25.81	33.41	37.35	39.32	35.28	34.63	22.29	23.82	35.84	39.25
4	37.67	24.93	32.32	36.22	38.42	34.20	33.83	22.03	23.66	34.82	38.36
5	36.27	24.11	31.18	34.94	37.32	32.97	32.86	21.74	23.47	33.70	37.26
6	34.74	23.31	30.01	33.57	36.07	31.70	31.76	21.43	23.27	32.51	36.02
7	33.14	22.53	28.83	32.16	34.73	30.42	30.61	21.10	23.04	31.30	34.69

8	31.54	21.78	27.67	30.80	33.34	29.15	29.45	20.81	22.81	30.15	33.31
9	30.05	21.09	26.55	29.49	31.95	27.91	28.28	20.54	22.56	29.01	31.92

Table 4.19 presents the variation in vehicle operation cost (NPR/veh-km) for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 6,520 PCU (-30% of the base volume). For cars, the operation cost rises from NPR 17.95 to 23.08, while heavy trucks show an increase from NPR 98.57 to 124.70, and light trucks from NPR 44.77 to 58.21. The operation cost for medium buses increases from NPR 49.16 to 61.73, microbuses from NPR 38.92 to 51.44, and small buses from NPR 38.40 to 47.68. Motorcycles show an increase from NPR 3.63 to 4.37, three-wheelers from NPR 13.79 to 16.02, and tractors from NPR 25.94 to 28.75. For utility vehicles, the operation cost rises from NPR 23.90 to 30.20, and for jeeps, from NPR 23.58 to 30.79.

Table:4.19 Vehicle operation cost sensitivity to roughness at -30% traffic volume (AADT) 6520 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	17.95	98.57	44.77	49.16	38.92	38.40	3.63	13.79	25.94	23.90	23.58
3	18.18	101.11	45.73	50.01	39.36	39.13	3.67	13.93	26.17	24.29	23.85
4	18.71	104.78	47.33	51.67	40.90	40.27	3.76	14.18	26.48	25.03	24.62
5	19.38	108.70	49.18	53.51	42.69	41.55	3.86	14.48	26.83	25.90	25.58
6	20.21	112.81	51.28	55.48	44.73	42.96	3.98	14.84	27.24	26.91	26.77
7	21.12	116.84	53.53	57.54	46.90	44.48	4.11	15.23	27.74	27.97	28.07
8	22.09	120.74	55.88	59.59	49.16	46.09	4.24	15.63	28.25	29.08	29.43
9	23.08	124.70	58.21	61.73	51.44	47.68	4.37	16.02	28.75	30.20	30.79

Table 4.20 presents the variation in travel time cost (NPR/veh-km) for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 6,520 PCU (-30% of the base volume). For cars, the travel time cost rises from NPR 6.69 to 8.87. The travel time cost for medium buses increases from NPR 63.14 to 82.16, microbuses from NPR 13.41 to 16.81, and small buses from NPR 41.59 to 54.16. Motorcycles show an increase from NPR 3.05 to 3.81, three-wheelers from

NPR 12.14 to 13.36, and tractors from NPR 2.04 to 2.17. For utility vehicles, the travel time cost rises from NPR 6.36 to 8.07, and for jeeps, from NPR 6.66 to 8.34.

Table 4.20 Travel time cost sensitivity to roughness at -30% traffic volume (AADT) 6520 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	6.69	1.77	1.36	63.14	13.41	41.59	3.05	12.14	2.04	6.36	6.66
3	6.84	1.83	1.40	64.67	13.64	42.63	3.10	12.25	2.05	6.51	6.77
4	7.06	1.89	1.45	66.69	13.96	43.99	3.18	12.39	2.07	6.70	6.93
5	7.33	1.96	1.50	69.16	14.38	45.63	3.27	12.55	2.08	6.93	7.14
6	7.66	2.03	1.56	72.02	14.88	47.48	3.38	12.73	2.10	7.19	7.39
7	8.03	2.10	1.63	75.16	15.46	49.54	3.51	12.92	2.12	7.46	7.67
8	8.44	2.17	1.70	78.54	16.11	51.77	3.66	13.13	2.14	7.76	7.99
9	8.87	2.25	1.77	82.16	16.81	54.16	3.81	13.36	2.17	8.07	8.34

Table 4.21 presents the variation in road user cost (RUC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 6,520 PCU (-30% of the base volume). For cars, the RUC rises from NPR 24.64 to 31.95, while heavy trucks remain steady at NPR 100.34to 126.95, and light trucks increase from NPR 46.13 to 59.98. The RUC for medium buses rises from NPR 112.31 to 143.89, microbuses from NPR 52.33 to 68.25, and small buses from NPR 79.99 to 101.84. Motorcycles show an increase from NPR 6.68 to 8.18, three-wheelers from NPR 25.93 to 29.38, and tractors from NPR 27.98 to 30.92. For utility vehicles, RUC rises from NPR 30.26 to 38.27, and for jeeps, from NPR 30.24 to 39.13.

Table:4.21 Road user cost sensitivity to roughness at -30% traffic volume (AADT) 6520 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	24.64	100.34	46.13	112.31	52.33	79.99	6.68	25.93	27.98	30.26	30.24
3	25.02	102.94	47.13	114.68	53.00	81.76	6.77	26.18	28.22	30.80	30.63
4	25.77	106.67	48.78	118.36	54.86	84.26	6.93	26.57	28.54	31.74	31.55
5	26.71	110.66	50.68	122.67	57.07	87.18	7.13	27.03	28.91	32.83	32.72
6	27.87	114.84	52.84	127.50	59.61	90.44	7.36	27.57	29.34	34.09	34.16

7	29.16	118.94	55.16	132.70	62.36	94.01	7.62	28.15	29.86	35.43	35.74
8	30.53	122.91	57.58	138.13	65.27	97.86	7.90	28.77	30.40	36.84	37.43
9	31.95	126.95	59.98	143.89	68.25	101.84	8.18	29.38	30.92	38.27	39.13

Table 4.22 presents the variation in average vehicle operating speed for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 6,520 PCU (-30% of the base volume). For cars, the average operating speed decreases from 42.02 km/h to 31.45 km/h, while heavy trucks slow down from 27.46 km/h to 21.39 km/h, and light trucks from 36.08 km/h to 27.46 km/h. The average speed for medium buses decreases from 40.38 km/h to 30.80 km/h, microbuses from 42.30 km/h to 33.59 km/h, and small buses from 38.08 km/h to 29.00 km/h. Motorcycles experience a reduction in speed from 37.04 km/h to 29.44 km/h, three-wheelers from 22.80 km/h to 20.68 km/h, and tractors from 24.24 km/h to 22.84 km/h. For utility vehicles, the speed drops from 38.66 km/h to 30.27 km/h, and for jeeps, from 42.21 km/h to 33.56 km/h.

Table:4.22 Average vehicle operating speed sensitivity to roughness at -30% traffic volume (AADT) 6520 pcu(Kmph)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	42.02	27.46	36.08	40.38	42.30	38.08	37.04	22.80	24.24	38.66	42.21
3	41.06	26.54	35.07	39.41	41.58	37.14	36.40	22.58	24.12	37.74	41.50
4	39.78	25.61	33.90	38.19	40.61	35.96	35.54	22.32	23.96	36.64	40.53
5	38.26	24.67	32.63	36.80	39.41	34.64	34.49	22.03	23.77	35.42	39.35
6	36.59	23.75	31.32	35.30	38.06	33.24	33.31	21.72	23.56	34.13	38.00
7	34.85	22.92	29.99	33.78	36.60	31.80	32.04	21.38	23.34	32.83	36.55
8	33.12	22.14	28.70	32.27	35.09	30.38	30.74	21.03	23.10	31.53	35.06
9	31.45	21.39	27.46	30.80	33.59	29.00	29.44	20.68	22.84	30.27	33.56

Table 4.23 presents the variation in vehicle operation costs (VOC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 4,658 PCU (-50% of the base volume). For cars, the VOC increases from NPR 17.43 to 22.36, while heavy trucks show an increase from NPR 95.75 to 123.19, and light trucks from NPR 42.99 to 56.31. The VOC for medium

buses rises from NPR 47.32 to 59.53, microbuses from NPR 37.77 to 49.99, and small buses from NPR 37.20 to 46.23. Motorcycles show an increase from NPR 3.59 to 4.29, three-wheelers from NPR 13.58 to 15.85, and tractors from NPR 25.75 to 28.50. For utility vehicles, VOC rises from NPR 23.05 to 29.17, and for jeeps, from NPR 22.84 to 29.82.

Table:4.23 Vehicle operation cost sensitivity to roughness at -50% traffic volume (AADT) 4658 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	17.43	95.75	42.99	47.32	37.77	37.20	3.59	13.58	25.75	23.05	22.84
3	17.64	98.37	43.90	48.11	38.18	37.88	3.63	13.73	25.98	23.41	23.09
4	18.14	102.24	45.48	49.70	39.67	38.97	3.71	13.98	26.28	24.12	23.83
5	18.77	106.34	47.31	51.47	41.42	40.21	3.80	14.29	26.61	24.96	24.76
6	19.57	110.63	49.39	53.38	43.41	41.59	3.92	14.67	27.00	25.93	25.91
7	20.45	114.94	51.63	55.38	45.54	43.07	4.04	15.06	27.49	26.97	27.17
8	21.39	119.10	53.97	57.41	47.75	44.66	4.17	15.46	28.00	28.07	28.49
9	22.36	123.19	56.31	59.53	49.99	46.23	4.29	15.85	28.50	29.17	29.82

Table 4.24 illustrates the variation in travel time cost (TTC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 4,658 PCU (-50% of the base volume). For cars, the TTC increases from NPR 6.17 to 8.28. The TTC for medium buses rises from NPR 58.31 to 76.86, microbuses from NPR 12.36 to 15.61, and small buses from NPR 38.51 to 50.94. Motorcycles show an increase from NPR 2.83 to 3.58, three-wheelers from NPR 11.88 to 13.16, and tractors from NPR 2.01 to 2.13. For utility vehicles, TTC rises from NPR 5.89 to 7.57, and for jeeps, from NPR 6.14 to 7.74.

Table:4.24 Travel time cost sensitivity to roughness at -50% traffic volume (AADT) 4658 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	6.17	1.68	1.26	58.31	12.36	38.51	2.83	11.88	2.01	5.89	6.14
3	6.31	1.74	1.30	59.75	12.57	39.50	2.88	12.01	2.02	6.04	6.24
4	6.52	1.81	1.35	61.68	12.87	40.81	2.95	12.16	2.04	6.22	6.39
5	6.78	1.89	1.40	64.05	13.27	42.40	3.04	12.33	2.05	6.44	6.59

6	7.09	1.97	1.46	66.80	13.75	44.25	3.15	12.53	2.07	6.68	6.82
7	7.45	2.05	1.53	69.89	14.30	46.30	3.28	12.73	2.09	6.96	7.10
8	7.85	2.13	1.60	73.25	14.93	48.54	3.43	12.94	2.11	7.25	7.41
9	8.28	2.21	1.68	76.86	15.61	50.94	3.58	13.16	2.13	7.57	7.74

Table 4.25 presents the variation in road user cost (RUC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 4,658 PCU (-50% of the base volume). For cars, the RUC rises from NPR 23.60 to 30.65, while heavy trucks show an increase from NPR 97.43 to 125.40, and light trucks from NPR 44.25 to 57.99. The RUC for medium buses increases from NPR 105.62 to 136.39, microbuses from NPR 50.13 to 65.60, and small buses from NPR 75.71 to 97.17. Motorcycles show an increase from NPR 6.42 to 7.87, three-wheelers from NPR 25.46 to 29.01, and tractors from NPR 27.76 to 30.63. For utility vehicles, RUC rises from NPR 28.94 to 36.74, and for jeeps, from NPR 28.98 to 37.57.

Table:4.25 Road user cost sensitivity to roughness at -50% traffic volume (AADT) 4658 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	23.60	97.43	44.25	105.62	50.13	75.71	6.42	25.46	27.76	28.94	28.98
3	23.95	100.11	45.20	107.86	50.75	77.38	6.51	25.74	28.00	29.45	29.33
4	24.65	104.05	46.83	111.39	52.55	79.78	6.66	26.14	28.31	30.34	30.22
5	25.55	108.23	48.71	115.53	54.69	82.61	6.85	26.63	28.66	31.40	31.35
6	26.66	112.60	50.85	120.18	57.16	85.83	7.07	27.19	29.07	32.61	32.73
7	27.90	116.99	53.16	125.27	59.84	89.38	7.32	27.79	29.58	33.93	34.27
8	29.24	121.23	55.57	130.66	62.67	93.20	7.60	28.39	30.12	35.32	35.90
9	30.65	125.40	57.99	136.39	65.60	97.17	7.87	29.01	30.63	36.74	37.57

Table 4.26 presents the variation in average vehicle operating speed for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 4,658 PCU (-50% of the base volume). For cars, the average speed decreases from 44.84 km/h to 33.31 km/h, while heavy trucks show a decline from 28.69 km/h to 21.78 km/h, and light trucks from 38.31 km/h to 28.83 km/h. The average speed for medium buses decreases from 43.04 km/h to 32.58 km/h, microbuses from 45.15 km/h to 35.69 km/h, and small buses from 40.53 km/h to 30.57 km/h. Motorcycles show a decrease in speed from 39.33 km/h to 31.05 km/h, three-wheelers from 23.28 km/h to 20.99 km/h, and tractors from 24.58 km/h to 23.17 km/h. For utility vehicles, the average speed decreases from 41.13 km/h to 31.97 km/h, and for jeeps, from 45.05 km/h to 35.66 km/h.

Table:4.26 Average vehicle operating speed sensitivity to roughness at -50% traffic volume (AADT) 4658 pcu(Kmph)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	44.84	28.69	38.31	43.04	45.15	40.53	39.33	23.28	24.58	41.13	45.05
3	43.81	27.66	37.22	41.99	44.39	39.50	38.65	23.03	24.46	40.14	44.29
4	42.42	26.58	35.94	40.67	43.33	38.23	37.72	22.74	24.30	38.95	43.25
5	40.77	25.51	34.54	39.16	42.04	36.78	36.59	22.42	24.11	37.62	41.96
6	38.94	24.47	33.09	37.53	40.56	35.24	35.30	22.06	23.90	36.22	40.50
7	37.05	23.49	31.63	35.86	38.98	33.66	33.91	21.71	23.67	34.79	38.93
8	35.15	22.59	30.21	34.20	37.34	32.09	32.48	21.36	23.43	33.37	37.30
9	33.31	21.78	28.83	32.58	35.69	30.57	31.05	20.99	23.17	31.97	35.66

Table 4.27 presents the variation in vehicle operation cost (VOC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 2,793 PCU (-70% of the base volume). For cars, the VOC rises from NPR 17.11 to 21.83, while heavy trucks show an increase from NPR 93.36 to 121.54, and light trucks from NPR 41.70 to 54.69. The VOC for medium buses increases from NPR 46.05 to 57.83, microbuses from NPR 37.00 to 48.93, and small buses from NPR 36.38 to 45.07. Motorcycles show an increase from NPR 3.58 to 4.23, three-wheelers from NPR 13.31 to 15.68, and tractors from NPR 25.59 to 28.28. For utility vehicles, VOC rises from NPR 22.46 to 28.38, and for jeeps, from NPR 22.36 to 29.13

Table:4.27 Vehicle operation cost sensitivity to roughness at -70% traffic volume (AADT) 2793 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	17.11	93.36	41.70	46.05	37.00	36.38	3.58	13.31	25.59	22.46	22.36
3	17.29	95.93	42.57	46.80	37.38	37.03	3.61	13.47	25.81	22.80	22.59
4	17.77	99.75	44.09	48.33	38.83	38.07	3.68	13.73	26.11	23.48	23.30
5	18.37	103.87	45.88	50.03	40.54	39.25	3.77	14.05	26.44	24.29	24.20
6	19.13	108.20	47.91	51.86	42.49	40.58	3.88	14.44	26.81	25.22	25.32
7	19.98	112.65	50.10	53.80	44.57	42.01	4.00	14.85	27.29	26.24	26.54
8	20.89	117.08	52.40	55.76	46.73	43.54	4.12	15.27	27.79	27.31	27.83
9	21.83	121.54	54.69	57.83	48.93	45.07	4.23	15.68	28.28	28.38	29.13

Table 4.28 presents the variation in travel time cost (TTC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 2,793 PCU (-70% of the base volume). For cars, the TTC rises from NPR 5.78 to 7.82. The TTC for medium buses increases from NPR 54.75 to 72.66, microbuses from NPR 11.59 to 14.70, and small buses from NPR 36.22 to 48.28. Motorcycles show an increase from NPR 2.67 to 3.40, three-wheelers from NPR 11.55 to 12.96, and tractors from NPR 1.99 to 2.11. For utility vehicles, TTC rises from NPR 5.54 to 7.16, and for jeeps, from NPR 5.76 to 7.29.

Table:4.28 Travel time cost sensitivity to roughness at -70% traffic volume (AADT) 2793 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	5.78	1.61	1.19	54.75	11.59	36.22	2.67	11.55	1.99	5.54	5.76
3	5.92	1.67	1.23	56.13	11.79	37.17	2.72	11.69	2.00	5.68	5.85
4	6.12	1.74	1.27	57.98	12.08	38.43	2.79	11.85	2.01	5.86	6.00
5	6.37	1.82	1.32	60.26	12.45	39.97	2.87	12.04	2.03	6.07	6.18
6	6.67	1.90	1.38	62.91	12.91	41.76	2.98	12.25	2.04	6.31	6.41
7	7.02	1.98	1.45	65.89	13.44	43.76	3.10	12.47	2.06	6.57	6.67
8	7.41	2.07	1.52	69.16	14.04	45.94	3.24	12.71	2.08	6.86	6.97
9	7.82	2.16	1.59	72.66	14.70	48.28	3.40	12.96	2.11	7.16	7.29

Table 4.29 presents the variation in road user cost (RUC) per vehicle-kilometer for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 2,793 PCU (-70% of the base volume). For cars, the RUC rises from NPR 22.89 to 29.66, while heavy trucks show an increase from NPR 94.97 to 123.70, and light trucks from NPR 42.89 to 56.28. The RUC for medium buses increases from NPR 100.80 to 130.49, microbuses from NPR 48.58 to 63.63, and small buses from NPR 72.60 to 93.35. Motorcycles show an increase from NPR 6.25 to 7.63, three-wheelers from NPR 24.86 to 28.63, and tractors from NPR 27.58 to 30.39. For utility vehicles, RUC rises from NPR 28.01 to 35.54, and for jeeps, from NPR 28.12 to 36.42.

Table:4.29 Road user cost sensitivity to roughness at -70% traffic volume (AADT) 2793 pcu(NPR/veh-km)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	Tr	Ut	J
2	22.89	94.97	42.89	100.80	48.58	72.60	6.25	24.86	27.58	28.01	28.12
3	23.21	97.60	43.80	102.93	49.16	74.20	6.33	25.16	27.81	28.48	28.45
4	23.88	101.49	45.36	106.31	50.91	76.50	6.47	25.58	28.12	29.34	29.30
5	24.74	105.69	47.20	110.29	52.99	79.22	6.65	26.09	28.47	30.36	30.38
6	25.80	110.10	49.29	114.77	55.40	82.34	6.86	26.68	28.86	31.53	31.73
7	27.00	114.63	51.55	119.70	58.01	85.77	7.10	27.32	29.35	32.81	33.22
8	28.30	119.15	53.92	124.92	60.77	89.48	7.36	27.99	29.88	34.16	34.80
9	29.66	123.70	56.28	130.49	63.63	93.35	7.63	28.63	30.39	35.54	36.42

Table 4.30 presents the variation in average vehicle operating speed for different vehicle categories as the International Roughness Index (IRI) increases from 2 to 9 m/km, at a reduced traffic volume of 2,793 PCU (-70% of the base volume). For cars, the average speed decreases from 47.46 km/h to 35.05 km/h, while heavy trucks show a decrease from 29.89 km/h to 22.23 km/h, and light trucks from 40.39 km/h to 30.20 km/h. The average speed for medium buses decreases from 45.52 km/h to 34.27 km/h, microbuses from 47.80 km/h to 37.66 km/h, and small buses from 42.80 km/h to 32.09 km/h. Motorcycles show a decrease from 41.44 km/h to 32.59 km/h, three-wheelers from 23.91 km/h to 21.32 km/h, and tractors from 24.88 km/h to 23.46 km/h. For utility vehicles, the average speed decreases from 43.42 km/h to 33.60 km/h, and for jeeps, from 47.68 km/h to 37.62 km/h

Table:4.30 Average vehicle operating speed sensitivity to roughness at -70% traffic volume (AADT) 2793 pcu(Kmph)

IRI	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
2	47.46	29.89	40.39	45.52	47.80	42.80	41.44	23.91	24.88	43.42	47.68
3	46.36	28.78	39.22	44.39	46.99	41.70	40.73	23.64	24.75	42.36	46.88
4	44.87	27.62	37.84	42.97	45.86	40.33	39.74	23.31	24.59	41.08	45.77
5	43.09	26.46	36.33	41.35	44.47	38.78	38.53	22.95	24.40	39.66	44.39
6	41.13	25.33	34.77	39.60	42.89	37.11	37.15	22.56	24.19	38.16	42.82
7	39.08	24.24	33.21	37.80	41.19	35.41	35.66	22.15	23.96	36.62	41.13
8	37.04	23.20	31.68	36.01	39.43	33.73	34.13	21.72	23.72	35.09	39.38
9	35.05	22.23	30.20	34.27	37.66	32.09	32.59	21.32	23.46	33.60	37.62

4.5.1.1.1 Total annual road user cost sensitivity to roughness across all vehicles

The annual vehicle operating cost (VOC), travel time cost (TTC), road user cost (RUC), and average vehicle operating speeds for all vehicle types were calculated and compared across international roughness index (IRI) values ranging from 2 m/km to 9 m/km, for traffic volumes reduced from 0% to –70% of the baseline.

Table 4.31 presents the sensitivity of total annual vehicle operation cost (VOC) to varying levels of road roughness (IRI) and reductions in traffic volume. As the IRI increases from 2 to 9 m/km, VOC rises under all traffic conditions. At baseline traffic (0%), the VOC increases from 106.39 million NPR at IRI 2 to 133.30 million NPR at IRI 9. Similarly, at reduced traffic levels, the VOC also increases with IRI; however, the total cost is significantly lower compared to the baseline. For instance, at IRI 2, VOC decreases from 106.39 million at 0% reduction to 27.04 million NPR at a 70% traffic reduction. A comparable trend is observed at IRI 9, where VOC falls from 133.30 million to 34.90 million NPR with the same reduction. These results clearly demonstrate that while road roughness increases vehicle operation costs, a decline in traffic volume leads to a considerable reduction in the total annual VOC, reflecting the combined influence of pavement condition and traffic intensity on operational expenditure.

Table 4.31: Vehicle operation cost sensitivity to roughness at different traffic level (in millions/km)

IRI/Traffic	0%	-10%	-30%	-50%	-70%
2	106.39	87.95	66.58	46.14	27.04
3	108.23	89.54	67.81	47.00	27.53
4	111.64	92.43	70.03	48.58	28.45
5	115.48	95.64	72.56	50.38	29.51
6	119.72	99.22	75.39	52.40	30.70
7	124.20	103.01	78.37	54.53	31.97
8	128.79	106.89	81.41	56.72	33.28
9	133.30	110.73	84.48	58.91	34.90

Table 4.32 shows the sensitivity of total annual Travel Time Cost (TTC) per kilometer (in millions of NPR) to changes in road roughness (IRI) and varying levels of traffic volume reduction. As IRI increases from 2 to 9 m/km, TTC consistently rises under all traffic conditions. At the baseline traffic level (0%), TTC increases from 54.91 million NPR/km at IRI 2 to 68.39 million NPR/km at IRI 9. However, as traffic volume decreases, the overall TTC reduces significantly. For example, at IRI 2, TTC drops from 54.91 million to 9.88 million NPR/km with a 40% traffic reduction. A similar trend is observed at IRI 9, where TTC decreases from 68.39 million to 12.86 million NPR/km. These results highlight that while deteriorating road conditions contribute to higher travel time costs, reductions in traffic volume substantially lessen the overall annual TTC.

Table 4.32: Travel time cost sensitivity to roughness at different traffic level (in millions/km)

IRI/Traffic	0%	-10%	-30%	-50%	-70%
2	54.91	35.86	26.18	17.43	9.88
3	56.02	36.57	26.74	17.81	10.09
4	57.47	37.52	27.47	18.32	10.39
5	59.20	38.68	28.37	18.94	10.75
6	61.18	40.00	29.41	19.67	11.18
7	63.39	41.45	30.57	20.49	11.66
8	65.81	43.00	31.84	21.39	12.19
9	68.39	44.63	33.19	22.36	12.86

Table 4.33 presents the sensitivity of total annual Road User Cost (RUC) per kilometer (in millions of NPR) to varying levels of road roughness (IRI) and reductions in traffic volume. The results indicate a clear trend of increasing RUC with higher IRI values under all traffic conditions. At baseline traffic (0%), the RUC rises from 161.30 million NPR/km at IRI 2 to 201.69 million NPR/km at IRI 9. However, as traffic volume decreases, the overall RUC declines significantly. For instance, at IRI 2, the RUC drops from 161.30 million to 36.91 million NPR/km with a 40% traffic reduction. Similarly, at IRI 9, it decreases from 201.69 million to 47.76 million NPR/km. These findings highlight that while increased road roughness leads to higher road user costs, reductions in traffic volume significantly mitigate the total annual RUC.

Table 4.33: Road user cost sensitivity to roughness at different traffic level (millions/km)

IRI/Traffic	0%	-10%	-30%	-50%	-70%
2	161.30	123.81	92.76	63.57	36.91
3	164.26	126.12	94.55	64.81	37.63
4	169.10	129.95	97.50	66.90	38.84
5	174.68	134.32	100.93	69.32	40.26
6	180.90	139.22	104.80	72.07	41.88
7	187.59	144.46	108.94	75.03	43.63
8	194.60	149.89	113.25	78.11	45.47
9	201.69	155.35	117.67	81.27	47.76

4.5.1.2 Road User Cost Sensitivity to Gradient and Curvature

In this part of the analysis, the IRI value was kept constant at 5.87 m/km. The road gradient (rise/fall per km) and curvatures were varied proportionally by 0%, 50%, and 100% at three levels: 20, 30, and 40 m/km for gradient, and 203, 305, and 406 degrees per kilometer for curvature. For each combination of gradient and curvature, the corresponding road user costs and average vehicle operating speeds were tabulated in Tables 4.33 to 4.52 to evaluate their impact under a fixed roughness condition. The notations used for each vehicle are C=car, HT=Heavy Truck, LT= Light Truck, MB=Medium Bus, MiB=Micro Bus, SB=Small Bus, MC=Motor Cycle, TW=Three Wheelers, T=Tractor, U= Utilities, J=Jeep

Table 4.34 presents the vehicle operation costs (NPR/veh-km) under different combinations of road gradient (G) and horizontal curvature (C) with a traffic volume of 9311 pcu (AADT). The analysis shows that as both gradient and curvature increase, the vehicle operation costs also rise for all vehicle categories. For example, at a gradient of 20 m/km and curvature of 203 degrees, the costs for a car is 21.11 NPR/veh-km, while for a heavy truck, the cost is 114.57 NPR/veh-km. When the gradient increases to 30 m/km and curvature to 305 degrees, the cost for a car rises to 22.09 NPR/veh-km, and for a heavy truck, it increases to 124.00 NPR/veh-km. At the highest gradient of 40 m/km and curvature of 406 degrees, the costs further increase, with a car costing 23.37 NPR/veh-km and a heavy truck costing 136.79 NPR/veh-km. This trend is consistent across all vehicle categories, indicating that both gradient and curvature significantly influence vehicle operating costs.

Table:4.34 Vehicle operation cost sensitivity to gradient and curvature at traffic volume (AADT) 9311 pcu(NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	21.11	114.57	53.40	58.25	46.58	44.65	4.06	15.02	27.54	28.14	28.03
30/ 305	22.09	124.00	57.83	66.01	48.89	48.83	4.15	15.33	32.97	29.94	29.60
40/ 406	23.37	136.79	63.67	74.58	51.69	58.39	4.29	15.63	36.97	32.02	31.53

Table 4.35 presents the travel time costs (NPR/veh-km) under different combinations of road gradient (G) and horizontal curvature (C) at a traffic volume of 9311 pcu (AADT). The data reveals a clear increasing trend in travel time costs as both the gradient and curvature increase across various vehicle categories. For instance, at a gradient of 20 m/km and curvature of 203 degrees, the travel time cost for a car is 8.46 NPR/veh-km, while the cost for a medium bus is 78.96 NPR/veh-km, and for a micro bus, it is 16.58 NPR/veh-km. When the gradient increases to 30 m/km and curvature to 305 degrees, the car's travel time cost rises to 9.29 NPR/veh-km, while medium buses see an increase to 87.29 NPR/veh-km. At the highest gradient of 40 m/km and curvature of 406 degrees, the cost further increases, with the car's travel time cost reaching 10.24 NPR/veh-km, and the medium bus's cost rising to 96.48 NPR/veh-km. This trend is consistent across all vehicle categories, with travel time costs rising as the gradient and curvature increase.

Table:4.35 Travel time cost sensitivity to gradient and curvature at traffic volume (AADT) 9311 pcu(NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	8.46	2.08	1.67	78.96	16.58	51.46	3.68	12.97	2.14	7.84	8.23
30/ 305	9.29	2.24	1.84	87.29	18.35	57.05	3.98	13.32	2.49	8.62	9.09
40/ 406	10.24	2.35	2.02	96.48	20.35	73.00	4.34	13.65	2.52	9.46	10.07

Table 4.36 presents the road user costs (NPR/veh-km) for different combinations of road gradient (G) and horizontal curvature (C) at a traffic volume of 9311 pcu (AADT). The data reveals a clear pattern of increasing road user costs as both the gradient and curvature increase for all vehicle categories. For example, at a gradient of 20 m/km and curvature of 203 degrees, the road user cost for a car is 29.57 NPR/veh-km, while for a heavy truck, it is 116.65 NPR/veh-km. When the gradient rises to 30 m/km and curvature increases to 305 degrees, the cost for a car rises to 31.38 NPR/veh-km, and for a heavy truck, it increases to 126.24 NPR/veh-km. At the highest gradient of 40 m/km and curvature of 406 degrees, the costs continue to rise, with a car costing 33.62 NPR/veh-km and a heavy truck costing 139.14 NPR/veh-km. The trend is consistent across all vehicle categories. This shows that both road gradient and curvature have a substantial impact on road user costs, especially for heavier and larger vehicles.

Table:4.36 Road user cost sensitivity to gradient and curvature at traffic volume (AADT) 9311 pcu(NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	29.57	116.65	55.07	137.22	63.16	96.11	7.74	27.99	29.68	35.98	36.26
30/ 305	31.38	126.24	59.67	153.30	67.24	105.88	8.13	28.65	35.46	38.55	38.69
40/ 406	33.62	139.14	65.69	171.06	72.04	131.39	8.62	29.28	39.48	41.48	41.60

Table 4.37 shows the average vehicle operating speeds (km/h) under different combinations of road gradient (G) and horizontal curvature (C) at a traffic volume of 9311 pcu (AADT). The results indicate that as both gradient and curvature increase, the average vehicle operating speeds decrease for all vehicle categories. For instance, at a gradient of 20 m/km and curvature of 203 degrees, the average speed for a car is 33.98 km/h, while for a heavy truck, it is 23.17 km/h. When the gradient increases to 30 m/km and curvature to 305 degrees, the car's speed decreases to 30.73 km/h, and the heavy truck's speed drops to 21.51 km/h. At the highest gradient of 40 m/km and curvature of 406 degrees, the car's speed further decreases to 27.84 km/h, and the heavy truck's speed to 20.48 km/h. This pattern of decreasing speeds is consistent across all vehicle categories. his trend highlights the

negative impact of increased gradient and curvature on vehicle operating speeds, particularly for heavier vehicles.

Table:4.37 Average vehicle operating speed sensitivity to gradient and curvature at traffic volume (AADT) 9311 pcu(Kmph)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	33.98	23.17	29.53	32.90	35.17	31.16	31.19	21.32	23.13	31.89	35.12
30/ 305	30.73	21.51	26.66	29.53	31.50	27.92	28.68	20.76	19.85	28.82	31.51
40/ 406	27.84	20.48	24.25	26.64	28.33	21.25	26.32	20.25	19.64	26.19	28.39

Table 4.38 presents the vehicle operation costs (NPR/veh-km) under different combinations of road gradient (G) and horizontal curvature (C) at a -10% traffic volume (AADT). The data show a consistent increase in vehicle operation costs as both gradient and curvature increase. At a gradient of 20 m/km and curvature of 203 degrees, the cost for a car is 20.73 NPR/veh-km, while for a heavy truck, it is 113.76 NPR/veh-km. When the gradient rises to 30 m/km and curvature to 305 degrees, the car's cost increases to 21.76 NPR/veh-km, and the heavy truck's cost rises to 123.12 NPR/veh-km. At the highest gradient of 40 m/km and curvature of 406 degrees, the cost further increases, with the car costing 23.00 NPR/veh-km and the heavy truck costing 136.39 NPR/veh-km.

Table:4.38 Vehicle operation cost sensitivity to gradient and curvature at -10% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	20.73	113.76	52.60	57.19	45.76	44.05	4.03	14.94	27.40	27.68	27.47
30/ 305	21.76	123.12	57.06	65.00	48.23	48.15	4.11	15.28	32.93	29.47	29.15
40/ 406	23.00	136.39	63.10	73.54	50.93	58.15	4.24	15.58	36.94	31.58	31.01

Table 4.39 presents the travel time costs (NPR/veh-km) under different combinations of road gradient (G) and horizontal curvature (C) at a -10% traffic volume (AADT). As both the gradient and curvature increase, the travel time costs tend to rise, with notable variations across vehicle categories. At a gradient of 20 m/km and curvature of 203 degrees, the travel time cost for a car is 8.15 NPR/veh-km, while for a heavy truck, it is 2.06 NPR/veh-km. For medium buses, the cost is 76.42 NPR/veh-km, and for micro buses, it is 15.91 NPR/veh-km. When the gradient rises to 30 m/km and curvature to 305 degrees, the car's travel time cost increases to 9.03 NPR/veh-km, while medium buses see a rise in cost to 84.92 NPR/veh-km. At the highest gradient of 40 m/km and curvature of 406 degrees, the cost further increases, with the car's travel time cost reaching 9.95 NPR/veh-km, and the medium bus's cost reaching 94.10 NPR/veh-km.

Table:4.39 Travel time cost sensitivity to gradient and curvature at -10% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	8.15	2.06	1.63	76.42	15.91	50.13	3.58	12.87	2.13	7.61	7.89
30/ 305	9.03	2.21	1.81	84.92	17.82	55.56	3.88	13.27	2.49	8.39	8.83
40/ 406	9.95	2.34	1.99	94.10	19.75	72.60	4.23	13.59	2.52	9.25	9.77

Table 4.40 presents the road user costs (NPR/veh-km) under varying combinations of road gradient (G) and horizontal curvature (C), at a traffic volume of 9,311 PCU (AADT) with a 10% reduction. The results show that as both gradient and curvature increase, road user costs rise consistently across all vehicle categories. For example, at a gradient of 20 m/km and a curvature of 203 degrees/km, the road user cost for a heavy truck is NPR 115.82/veh-km, and for a car, it is NPR 28.88/veh-km. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the cost rises to NPR 125.33 for heavy trucks and NPR 30.79 for cars. At the highest tested gradient of 40 m/km and curvature of 406 degrees/km, the cost further increases to NPR 138.73 for heavy trucks and NPR 32.96 for cars. A similar increasing trend is observed across all other vehicle types, indicating the significant influence of road geometry on road user costs.

Table:4.40 Road user cost sensitivity to gradient and curvature at -10% traffic volume(NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	28.88	115.82	54.23	133.61	61.66	94.18	7.61	27.81	29.53	35.29	35.37
30/ 305	30.79	125.33	58.87	149.92	66.05	103.71	7.99	28.55	35.42	37.86	37.98
40/ 406	32.96	138.73	65.09	167.65	70.68	130.75	8.48	29.17	39.46	40.83	40.79

Table 4.41 presents the average vehicle operating speeds (km/h) under varying combinations of road gradient (G, in m/km) and horizontal curvature (C, in degrees/km), at a traffic volume of 9,311 PCU (AADT) with a 10% reduction. The results show that as both gradient and curvature increase, average vehicle speeds decrease consistently across all categories. At a gradient of 20 m/km and curvature of 203 degrees/km, the operating speed of a car is 33.98 km/h, while that of a heavy truck is 23.17 km/h. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the speed drops to 30.73 km/h for cars and 21.51 km/h for heavy trucks. At the highest tested combination of 40 m/km gradient and 406 degrees/km curvature, the average speed further decreases to 27.84 km/h for cars and 20.48 km/h for heavy trucks. A similar decreasing trend is observed across all other vehicle types, reflecting the strong influence of road geometry on vehicle operating speeds.

Table:4.41 Average vehicle operating speed sensitivity to gradient and curvature at -10% traffic volume (Kmph)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	33.98	23.17	29.53	32.90	35.17	31.16	31.19	21.32	23.13	31.89	35.12
30/ 305	30.73	21.51	26.66	29.53	31.50	27.92	28.68	20.76	19.85	28.82	31.51
40/ 406	27.84	20.48	24.25	26.64	28.33	21.25	26.32	20.25	19.64	26.19	28.39

Table 4.42 presents vehicle operating costs (VOC) in NPR per vehicle-kilometer under varying combinations of road gradient (G, in meters per kilometer) and horizontal curvature (C, in degrees per kilometer), at a traffic volume reduced by 30%. The results show that VOC increases consistently across all vehicle categories with rising gradient and curvature. At a gradient of 20 m/km and curvature of 203 degrees/km, the VOC for a car is NPR 20.09/veh-km, and for a heavy truck, it is NPR 112.27/veh-km. When the gradient and curvature increase to 30 m/km and 305 degrees/km, the VOC rises to NPR 21.07 for cars and NPR 121.58 for heavy trucks. At the highest tested combination of 40 m/km gradient and 406 degrees/km curvature, VOC increases further to NPR 22.30 for cars and NPR 135.61 for heavy trucks. Similar increasing trends are observed for all other vehicle types, demonstrating the substantial impact of road geometry on vehicle operating costs.

Table:4.42 Vehicle operation cost sensitivity to gradient and curvature at -30% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	20.09	112.27	51.00	55.22	44.46	42.77	3.96	14.79	27.18	26.77	26.61
30/ 305	21.07	121.58	55.56	63.02	46.81	46.99	4.04	15.12	32.86	28.56	28.19
40/ 406	22.30	135.61	61.72	71.54	49.53	57.52	4.16	15.48	36.89	30.64	30.05

Table 4.43 presents the travel time costs (TTC) in NPR per vehicle-kilometer under different combinations of road gradient (G, in meters per kilometer) and horizontal curvature (C, in degrees per kilometer), at a 30% reduced traffic volume. The data shows that as gradient and curvature increase, TTC also rises across all passenger-carrying vehicle categories. At a gradient of 20 m/km and curvature of 203 degrees/km, TTC for a car is NPR 7.62/veh-km, while for a medium bus, it is NPR 71.62/veh-km. When the gradient increases to 30 m/km and curvature to 305 degrees/km, TTC rises to NPR 8.47 for cars and NPR 80.22 for medium buses. At the highest tested level of 40 m/km gradient and 406 degrees/km curvature, TTC increases further to NPR 9.40 for cars and NPR 89.44 for medium buses. Similar increases are observed for other passenger vehicles such as microbuses, small buses, motorcycles, utilities, and jeeps.

Table:4.43 Travel time cost sensitivity to gradient and curvature at -30% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	7.62	2.02	1.55	71.62	14.81	47.22	3.37	12.70	2.10	7.15	7.35
30/ 305	8.47	2.17	1.73	80.22	16.66	53.00	3.68	13.09	2.48	7.95	8.25
40/ 406	9.40	2.32	1.91	89.44	18.61	71.40	4.03	13.49	2.52	8.81	9.21

Table 4.44 presents the road user cost (RUC) in NPR per vehicle-kilometer under varying combinations of road gradient (G, in meters per kilometer) and horizontal curvature (C, in degrees per kilometer), at a traffic volume reduced by 30%. The results indicate that RUC increases consistently with rising gradient and curvature across all vehicle types. At a gradient of 20 m/km and curvature of 203 degrees/km, the RUC for a car is NPR 27.71/veh-km, and for a heavy truck, it is NPR 114.29/veh-km. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the RUC rises to NPR 29.54 for cars and NPR 123.75 for heavy trucks. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the RUC reaches NPR 31.71 for cars and NPR 137.93 for heavy trucks. Similar increasing trends are observed for all other vehicle categories indicating a significant impact of road geometry on overall road user costs.

Table:4.44 Road user cost sensitivity to gradient and curvature at -30% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	27.71	114.29	52.55	126.84	59.27	90.00	7.33	27.49	29.28	33.92	33.96
30/ 305	29.54	123.75	57.29	143.24	63.47	99.99	7.71	28.21	35.35	36.51	36.44
40/ 406	31.71	137.93	63.63	160.98	68.14	128.91	8.19	28.97	39.41	39.45	39.25

Table 4.45 presents the average vehicle operating speed (in km/h) under varying combinations of road gradient (G, in meters per kilometer) and horizontal curvature (C, in degrees per kilometer), at a traffic volume reduced by 30%. The results show a consistent decrease in vehicle operating speed with increasing gradient and curvature across all vehicle types. At a gradient of 20 m/km and curvature of 203 degrees/km, the average speed for a car is 36.81 km/h, while for a heavy truck, it is 23.87 km/h. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the average speed decreases to 33.11 km/h for cars and 22.19 km/h for heavy trucks. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the speed further reduces to 29.94 km/h for cars and 20.77 km/h for heavy trucks. Similar decreasing trends in operating speed are observed for all other vehicle categories, highlighting the negative impact of road geometry on vehicle speed, particularly for larger vehicles such as trucks and buses.

Table:4.45 Average vehicle operating speed sensitivity to gradient and curvature at -30% traffic volume (Kmph)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/203	36.81	23.87	31.49	35.50	38.24	33.42	33.46	21.76	23.59	34.30	38.19
30/305	33.11	22.19	28.25	31.68	34.02	29.76	30.67	21.13	19.91	30.84	34.03
40/406	29.94	20.77	25.50	28.49	30.54	21.73	28.09	20.50	19.64	27.93	30.60

Table 4.46 presents the vehicle operation cost (VOC) in NPR per vehicle-kilometer under varying combinations of road gradient (G, in meters per kilometer) and horizontal curvature (C, in degrees per kilometer), at a traffic volume reduced by 50%. The results indicate a consistent increase in vehicle operation costs with rising gradient and curvature across all vehicle types At a gradient of 20 m/km and curvature of 203 degrees/km, the VOC for a car is NPR 19.46/veh-km, while for a heavy truck, it is NPR 110.07/veh-km. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the VOC rises to NPR 20.31 for cars and NPR 119.86 for heavy trucks. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the VOC further increases to NPR 21.36 for cars and NPR 134.20 for heavy trucks. Similar upward trends in VOC are observed for all other

vehicle categories, demonstrating the significant impact of road geometry on vehicle operation costs, particularly for heavier vehicles like trucks and buses.

Table:4.46 Vehicle operation cost sensitivity to gradient and curvature at -50% traffic volume (NPR/veh-km)

G/C	G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U
20/ 203	19.46	110.07	49.11	53.12	43.15	41.40	3.90	14.62	26.95	25.80	25.75
30/ 305	20.31	119.86	53.60	60.64	45.27	45.44	3.96	14.89	32.77	27.45	27.16
40/ 406	21.36	134.20	59.71	68.73	47.70	56.58	4.05	15.26	36.84	29.32	28.79

Table 4.47 presents the travel time costs (TTC) in NPR per vehicle-kilometer under varying road gradients (G) and curvatures (C) at a 50% reduced traffic volume. As gradient and curvature increase, TTC rises across most vehicle categories, particularly for passenger vehicles. For example, at 20 m/km gradient and 203 degrees/km curvature, the TTC for a car is NPR 7.05, while for a medium bus, it is NPR 66.42. At 40 m/km gradient and 406 degrees/km curvature, the TTC increases to NPR 8.65 for cars and NPR 82.77 for medium buses. Motorcycles, three-wheelers, and tractors show smaller increases in TTC compared to buses.

Table:4.47 Travel time cost sensitivity to gradient and curvature at -50% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	7.05	1.96	1.45	66.42	13.68	43.99	3.14	12.50	2.07	6.65	6.79
30/ 305	7.84	2.12	1.63	74.48	15.38	49.46	3.42	12.82	2.47	7.40	7.62
40/ 406	8.65	2.27	1.81	82.77	17.10	69.47	3.73	13.22	2.52	8.16	8.46

Table 4.48 presents the road user costs (RUC) in NPR per vehicle-kilometer under varying combinations of road gradient (G) and curvature (C) at a 50% reduced traffic volume. The data shows that RUC increases with higher gradient and curvature across all vehicle types. At a gradient of 20 m/km and curvature of 203 degrees/km, the RUC for a car is NPR 26.51, while for a medium bus, it is NPR 119.55. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the RUC rises to NPR 28.14 for cars and NPR 135.12 for medium buses. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the RUC further increases to NPR 30.01 for cars and NPR 151.50 for medium buses. Similar increases are observed for other vehicles, demonstrating the significant impact of road geometry on road user costs, particularly for heavier vehicles like trucks and buses.

Table:4.48 Road user cost sensitivity to gradient and curvature at -50% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	26.51	112.03	50.56	119.55	56.83	85.39	7.04	27.12	29.02	32.45	32.54
30/ 305	28.14	121.98	55.23	135.12	60.65	94.90	7.38	27.71	35.24	34.85	34.77
40/ 406	30.01	136.47	61.52	151.50	64.80	126.04	7.78	28.48	39.35	37.48	37.25

Table 4.49 presents the average vehicle operating speeds (in km/h) under varying road gradients (G) and curvatures (C) at a 50% reduced traffic volume. The results show that average speeds decrease as both gradient and curvature increase across all vehicle types. At a gradient of 20 m/km and curvature of 203 degrees/km, the average speed for a car is 39.19 km/h, while for a medium bus, it is 37.75 km/h. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the speed for cars drops to 35.28 km/h and for medium buses to 33.69 km/h. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the speed for cars further decreases to 32.03 km/h, and for medium buses, it reaches 30.38 km/h. Similar reductions in speed are observed for other vehicle types, with motorcycles, three-wheelers, and tractors showing less pronounced reductions compared to larger vehicles like buses.

Table:4.49 Average vehicle operating speed sensitivity to gradient and curvature at -50% traffic volume (Kmph)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	39.19	24.60	33.28	37.75	40.76	35.44	35.47	22.11	23.93	36.40	40.70
30/ 305	35.28	22.73	29.79	33.69	36.29	31.55	32.55	21.57	19.99	32.74	36.31
40/ 406	32.03	21.18	26.85	30.38	32.70	22.31	29.95	20.91	19.64	29.75	32.77

Table 4.50 presents the vehicle operation costs (VOC) in NPR per vehicle-kilometer under varying combinations of road gradient (G) and curvature (C) at a 70% reduced traffic volume. The data shows that VOC increases as both gradient and curvature rise across all vehicle types. At a gradient of 20 m/km and curvature of 203 degrees/km, the VOC for a car is NPR 19.03, while for a medium bus, it is NPR 51.62. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the VOC rises to NPR 19.76 for cars and NPR 58.82 for medium buses. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the VOC further increases to NPR 20.66 for cars and NPR 66.45 for medium buses. Similar trends are observed for other vehicle types, with motorcycles, three-wheelers, and tractors showing smaller increases in VOC compared to passenger vehicles and heavy vehicles

Table:4.50 Vehicle operation cost sensitivity to gradient and curvature at -70% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	19.03	107.62	47.64	51.62	42.23	40.40	3.87	14.38	26.76	25.10	25.16
30/ 305	19.76	117.77	51.88	58.82	44.15	44.24	3.90	14.66	32.66	26.60	26.42
40/ 406	20.66	132.26	57.66	66.45	46.32	55.54	3.97	14.96	36.79	28.25	27.85

Table 4.51 presents the travel time costs (TTC) in NPR per vehicle-kilometer under varying combinations of road gradient (G) and curvature (C) at a 70% reduced traffic volume. The data indicates that TTC increases with higher gradient and curvature for passenger vehicles. At a gradient of 20 m/km and curvature of 203 degrees/km, the TTC for a car is NPR 6.63, while for a medium bus, it is NPR 62.55. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the TTC rises to NPR 7.35 for cars and NPR 69.97 for medium buses. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the TTC increases further to NPR 8.06 for cars and NPR 77.26 for medium uses. Motorcycles, three-wheelers, and tractors show smaller increases in TTC compared to buses.

Table:4.51 Travel time cost sensitivity to gradient and curvature at -70% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	6.63	1.89	1.38	62.55	12.85	41.51	2.96	12.22	2.04	6.27	6.38
30/ 305	7.35	2.05	1.53	69.97	14.41	46.55	3.22	12.53	2.46	6.96	7.14
40/ 406	8.06	2.21	1.70	77.26	15.93	67.19	3.49	12.87	2.52	7.63	7.88

Table 4.52 presents the road user costs (RUC) in NPR per vehicle-kilometer under varying combinations of road gradient (G) and curvature (C) at a 70% reduced traffic volume. The results show that RUC increases with higher gradient and curvature across all vehicle types. At a gradient of 20 m/km and curvature of 203 degrees/km, the RUC for a car is NPR 25.66, while for a medium bus, it is NPR 114.16. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the RUC rises to NPR 27.12 for cars and NPR 128.79 for medium buses. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the RUC further increases to NPR 28.73 for cars and NPR 143.72 for medium buses. Similar increasing trends are observed for other vehicle categories, with smaller increases for motorcycles, three-wheelers, and tractors compared to larger vehicles like buses. Heavy and light trucks also see higher RUCs, although the change is less pronounced compared to buses and passenger vehicles.

Table:4.52 Road user cost sensitivity to gradient and curvature at -70% traffic volume (NPR/veh-km)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	25.66	109.51	49.02	114.16	55.07	81.91	6.83	26.60	28.80	31.37	31.54
30/ 305	27.12	119.82	53.41	128.79	58.56	90.79	7.13	27.19	35.12	33.56	33.56
40/ 406	28.73	134.47	59.36	143.72	62.25	122.73	7.45	27.83	39.31	35.87	35.73

Table 4.53 presents the average vehicle operating speeds (VOS) in kilometers per hour (Kmph) under varying combinations of road gradient (G) and curvature (C) at a 70% reduced traffic volume. The data shows that average speed decreases with increasing gradient and curvature across all vehicle types. At a gradient of 20 m/km and curvature of 203 degrees/km, the VOS for a car is 41.39 kmph, while for a medium bus, it is 39.83 kmph. When the gradient increases to 30 m/km and curvature to 305 degrees/km, the VOS decreases to 37.33 kmph for cars and 35.61 kmph for medium buses. At the highest tested condition of 40 m/km gradient and 406 degrees/km curvature, the VOS further drops to 34.05 kmph for cars and 32.27 kmph for medium buses. Similar reductions are observed for other vehicle types, with motorcycles and jeeps showing slightly higher speeds compared to larger vehicles. Heavy trucks, light trucks, and buses experience more significant reductions in speed as road gradient and curvature increase

Table:4.53 Average vehicle operating speed sensitivity to gradient and curvature at -70% traffic volume (Kmph)

G/C	C	HT	LT	MB	MiB	SB	MC	TW	T	U	J
20/ 203	41.39	25.47	34.98	39.83	43.11	37.33	37.33	22.61	24.22	38.35	43.03
30/ 305	37.33	23.44	31.38	35.61	38.43	33.30	34.35	22.05	20.10	34.56	38.45
40/ 406	34.05	21.79	28.39	32.27	34.79	23.03	31.78	21.48	19.64	31.57	34.86

4.5.1.2.1 Total Road user cost sensitivity to gradient and curvature across all vehicles

The annual vehicle operating cost (VOC), travel time cost (TTC), road user cost (RUC), and average vehicle operating speeds for all vehicle types were calculated and compared across gradient and curvatures values ranging from 20 m/km and 203 degrees/km to 40 m/km and 406 degrees/km, for traffic volumes from 0% to -70%.

Table 4.54 presents the sensitivity of total annual Vehicle Operating Cost (VOC) per kilometer (in millions of NPR) to varying combinations of road gradient and curvature under different traffic levels. With traffic volume at 0%, VOC increases from 106.39 million NPR/km at gradient/curvature 20/203 to 141.77 million NPR/km at 40/406, reflecting the cost impact of steeper gradients and sharper curves. This pattern holds across all reduced traffic levels, although total VOC decreases as traffic volume declines. For example, at the highest gradient/curvature combination (40/406), VOC drops from 141.77 million at 0% reduction to 36.42 million NPR/km at a 70% traffic reduction. These results demonstrate that while higher gradient and curvature intensify vehicle operating costs, traffic reduction significantly lowers the overall annual VOC.

Table 4.54: VOC sensitivity to gradient/curvature at different traffic level (millions/km)

G/C/Traffic	0%	-10%	-30%	-50%	-70%
20/203	106.39	98.74	75.01	52.13	30.54
30/305	128.43	105.98	80.61	56.03	32.81
40/406	141.77	116.71	89.27	62.20	36.42

Table 4.55 illustrates the sensitivity of total annual Travel Time Cost (TTC) per kilometer (in millions of NPR) to variations in road gradient and curvature under different traffic volumes. At 0% traffic reduction, TTC increases from 54.91 million NPR/km at gradient/curvature 20/203 to 78.21 million NPR/km at 40/406, indicating that steeper gradients and sharper curves lead to longer travel times and higher time-related costs. Across all gradient-curvature combinations, TTC consistently decreases with declining traffic volumes. For example, at 40/406, TTC reduces from 78.21 million to 14.99 million NPR/km as traffic drops by 70%. These findings highlight that while geometric road design influences travel time costs, lower traffic volumes can significantly mitigate these impacts.

Table 4.55: TTC sensitivity to gradient/curvature at different traffic level (NPR/km)

G/C/Traffic	0%	-10%	-30%	-50%	-70%
20/203	54.91	39.82	29.27	19.57	11.12
30/305	67.26	43.77	32.40	21.66	12.28
40/406	78.21	51.30	38.61	26.22	14.99

Table 4.56 presents the sensitivity of total annual Road User Cost (RUC) per kilometer (in millions of NPR) to different combinations of road gradient and curvature under varying traffic volumes. At the baseline traffic level (0%), RUC increases from 161.30 million NPR/km at gradient/curvature 20/203 to 219.99 million NPR/km at 40/406, reflecting the compounded effect of steeper gradients and sharper curves on overall user costs. As traffic volume decreases, RUC declines across all geometric configurations. For instance, at 40/406, RUC drops from 219.99 million to 51.40 million NPR/km with a 70% traffic reduction.

Table 4.56: RUC sensitivity to gradient/curvature at different traffic level (NPR/km)

G/C/Traffic	0%	-10%	-30%	-50%	-70%
20/203	161.30	138.57	104.28	71.70	41.66
30/305	195.69	149.76	113.00	77.69	45.09
40/406	219.99	168.01	127.87	88.42	51.40

4.6. Improvement Scenario Assessment

The 8.53 km detour section of the BP Highway, surfaced with unsealed gravel and an average IRI of 20.59 m/km, significantly contributed to elevated Road User Costs (RUC) along the 45 km Dhulikhel–Barkhekhola corridor. To assess potential cost savings, an improvement scenario was modeled where the gravel detour was upgraded to a bituminous surface, reducing the IRI to 5.87 m/km consistent with the unaffected section. Using the HDM-4 framework, RUC was recalculated for the upgraded segment. The vehicles used are Car, heavy truck, light truck, medium bus, micro bus, small bus, motor cycle, three wheelers, tractor, utilities and jeep respectively (from top to bottom). The estimated annual savings in Vehicle Operating Cost (VOC), Travel Time Cost (TTC), and total RUC per kilometer for all vehicle categories, considering the 8.53 km detour as well as average costs across the entire 45 km section, are presented in Tables 4.60 and 4.61 and 4.62.

Table 4.57 presents the estimated annual Vehicle Operating Cost (VOC) savings from upgrading the 8.53 km gravel detour section of the BP Highway to a bituminous surface. The upgrade led to significant VOC reductions for all vehicle types on the detour itself, with savings ranging from 22.22% to 39.42%, and an overall reduction of 35.34%, decreasing the total VOC from 184.97 to 119.60 million NPR/km. When considering the average VOC over the entire 45 km section (including both detour and unaffected parts), the overall savings remained notable. The average VOC dropped from 131.19 to 119.02 million NPR/km, resulting in a net saving of 9.28%. These results highlight the economic justification for upgrading gravel detours to paved standards

Table:4.57 Total annual VOC savings from upgrading gravel detour to bituminous surface. (in millions/km)

Considering Detour (8.53 km)			Considering whole section (45 km)		
gravel detour	**After gravel detour upgrading to bituminous section**	**% saving**	**Average cost with gravel detour**	**Average Cost after gravel detour upgraded to bituminous**	**% saving**
21.54	13.60	36.86	15.02	13.55	9.79
48.40	33.94	29.88	36.38	33.69	7.39
7.45	4.79	35.70	5.26	4.77	9.32
25.72	15.81	38.53	17.59	15.75	10.46
24.05	15.46	35.72	17.01	15.41	9.41

29.73	18.01	39.42	20.13	17.95	10.83
5.11	3.42	33.07	3.73	3.41	8.58
0.18	0.14	22.22	0.15	0.14	6.67
0.23	0.15	34.78	0.16	0.14	12.50
10.15	6.53	35.67	7.17	6.49	9.48
12.41	7.75	37.55	8.59	7.72	10.13
184.97	**119.60**	**35.34**	**131.19**	**119.02**	**9.28**

Table 4.58 presents the total annual Travel Time Cost (TTC) savings resulting from upgrading the 8.53 km gravel detour to a bituminous surface. Significant cost reductions are observed across most vehicle types within the detoured section, with savings ranging from 15.28% to 34.70%, and an overall TTC reduction from 89.92 million NPR/km to 60.26 million NPR/km, reflecting a 32.98% decrease. When averaged over the entire 45 km section (including both detour and unaffected parts), the TTC drops from 65.27 million NPR/km to 61.14 million NPR/km, indicating a 6.33% overall saving. These results highlight the economic justification for upgrading gravel detours to paved standards

Table:4.58 Total annual TTC savings from upgrading gravel detour to bituminous surface. (in millions/km)

	Considering Detour (8.53 km)			**Considering whole section (45 km)**		
	gravel detour	**After gravel detour upgrading to bituminous section**	**% saving**	**Average cost with gravel detour**	**Average Cost after gravel detour upgraded to bituminous**	**% saving**
	8.27	5.40	34.70	5.89	5.34	9.34
	0.72	0.61	15.28	0.63	0.61	3.17
	0.21	0.15	28.57	0.16	0.15	6.25
	32.02	20.91	34.70	22.81	22.13	2.98
	8.09	5.44	32.76	5.89	5.40	8.32
	30.18	20.48	32.14	22.12	20.32	8.14
	4.35	3.08	29.20	3.28	3.04	7.32
	0.12	0.13	-8.33	0.12	0.12	0.00
	0.01	0.01	0.00	0.01	0.01	0.00
	2.61	1.80	31.03	1.93	1.79	7.25
	3.34	2.25	32.63	2.43	2.23	8.23
	89.92	**60.26**	**32.98**	**65.27**	**61.14**	**6.33**

Table 4.59 presents the total annual Road User Cost (RUC) savings achieved by upgrading the 8.53 km gravel detour section to a bituminous surface. Within the detour section, RUC reduced significantly from 274.89 million NPR/km to 179.86 million NPR/km, resulting in a 34.57% saving. When averaged across the entire 45 km corridor, the RUC declined from 196.46 million NPR/km to 180.16 million NPR/km, representing an 8.30% overall reduction.

Table:4.59 Total annual RUC savings from upgrading gravel detour to bituminous surface. (in millions/km)

Considering Detour (8.53 km)			**Considering whole section (45 km)**		
gravel detour	**After gravel detour upgrading to bituminous section**	**% saving**	**Average cost with gravel detour**	**Average Cost after gravel detour upgraded to bituminous**	**% saving**
29.81	19.00	36.26	20.91	18.89	9.66
49.12	34.55	29.66	37.01	34.30	7.32
7.66	4.94	35.51	5.42	4.92	9.23
57.74	36.72	36.40	40.40	37.88	6.24
32.14	20.90	34.97	22.90	20.81	9.13
59.91	38.49	35.75	42.25	38.27	9.42
9.46	6.50	31.29	7.01	6.45	7.99
0.30	0.27	10.00	0.27	0.26	3.70
0.24	0.16	33.33	0.17	0.15	11.76
12.76	8.33	34.72	9.10	8.28	9.01
15.75	10.00	36.51	11.02	9.95	9.71
274.89	**179.86**	**34.57**	**196.46**	**180.16**	**8.30**

The annual fuel cost savings for all vehicles resulting from upgrading the gravel detour to a bituminous surface considering the 8.53 km detour as well as average costs across the entire 45 km section, are presented in Tables 4.60

Table:4.60 Total annual fuel cost savings per km from upgrading gravel detour to bituminous surface.

Considering Detour(8.53 km)			Considering whole section(45 km)		
gravel detour	After gravel detour upgrading to bituminous section	% saving	Average cost with gravel detour	Average Cost after gravel detour upgraded to bituminous	% saving
81.72	51.14	37.42	56.56	50.88	10.06

Table 4.60 illustrates the total annual fuel cost savings per kilometer resulting from the upgrade of the 8.53 km gravel detour to a bituminous surface. The fuel cost within the detour section decreased significantly from 81.72 million NPR/km to 51.14 million NPR/km, representing a 37.42% saving. When averaged over the entire 45 km section, the fuel cost declined from 56.56 million NPR/km to 50.88 million NPR/km, yielding an overall reduction of 10.06%. This indicates that improving road surface conditions not only enhances vehicle performance but also contributes to substantial fuel savings

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This study assessed the impact of the 2024 disaster on road user costs (RUC) along the Dhulikhel–Barkhekhola segment of the BP Highway (NH13), using the HDM-4 model. The entire 45 km stretch was analyzed under both pre-disaster and post-disaster conditions. Before the disaster, the entire section consisted of continuous bituminous pavement. After the disaster, the road was divided into two distinct segments: an 8.53 km detour(gravel) and a 37.33 km unaffected (bituminous) section. Each segment was analyzed separately, and a weighted average was computed to represent the overall post-disaster scenario of the 45 km route. The costs presented in this analysis refer to the economic cost rather than the financial cost.

The analysis revealed that the increase in road user cost is primarily due to the 8.53 km detour, while the unaffected 37.33 km segment contributed little to no increase in costs. Prior to the disaster, the annual vehicle operating cost (VOC), travel time cost (TTC), and total annual road user cost (RUC) for the 45 km segment were NPR 118.79 million/km, NPR 60.48 million/km, and NPR 179.27 million/km, respectively. After the disaster, the weighted average VOC, TTC, and RUC increased to NPR 131.18 million/km, NPR 65.27 million/km, and NPR 196.46 million/km, respectively.

The detour, which constitutes only 19% of the total Dhulikhel–Barkhekhola route length (45 km), significantly impacted overall road user costs. Due to the disaster, the annual vehicle operating cost (VOC), travel time cost (TTC), and total road user cost (RUC) increased by NPR 12.39 million/km, NPR 4.79 million/km, and NPR 17.19 million/km, respectively.

Furthermore, a detailed analysis of the RUC components revealed that fuel costs were the dominant contributor, accounting for approximately 30% of the total cost. Following the disaster, annual fuel costs alone increased by NPR 6 million.

A sensitivity analysis was also conducted by varying key parameters such as traffic volume (ranging from 0% to -70%), the International Roughness Index (IRI)(ranging from 2m/km to 9 m/km), road gradient, and horizontal curvature(20,30 and 40 m/km for gradient and 203,305 and 406 degree per km for curvature). The results identified traffic volume, road surface condition (IRI), and geometric characteristics (gradient and curvature) as critical factors influencing total road user costs

An improvement scenario assessment was conducted by upgrading the 8.53 km gravel detour to a bituminous surface with an IRI value of 5.87. Following the upgrade, the weighted average annual vehicle operating cost (VOC), travel time cost (TTC), and total road user cost (RUC) decreased to NPR 119.02 million/km, NPR 61.14 million/km, and NPR 180.16 million/km, respectively. This corresponds to a total annual RUC savings of NPR 16.3 million/km. Additionally, annual fuel cost savings alone amounted to NPR 5.68 million. The results indicate that enhancing pavement quality from gravel to bituminous significantly reduces road user costs.

Considering the entire 45 km Dhulikhel–Barkhekhola section, the total annual road user cost increased by NPR 773.55 million due to the disaster. However, upgrading the 8.53 km gravel detour to a bituminous surface resulted in a total annual saving of NPR 733.5 million, highlighting the substantial economic benefit of timely surface improvement

This study showed that the condition of the road plays a critical role in determining road user costs. In Nepal, road surfaces often remain unsealed for extended periods following disasters, leading to significantly higher vehicle operating and travel time costs. The findings show that simply sealing damaged or detoured sections with bituminous surfaces can result in substantial cost savings, contributing positively to the national economy. This also emphasizes the importance of timely road maintenance and strongly advocates for the government to ensure the prompt and adequate allocation of funds for road infrastructure upkeep.

5.2 Recommendations

Following recommendations are considered:

1. This study was conducted under the assumption that traffic volume remained constant before and after the disaster. However, in reality, traffic patterns are likely to have changed due to the disruption, with a potential reduction in overall traffic and a shift of some vehicles to alternative routes. Therefore, it is recommended that future studies incorporate actual post-disaster traffic data to improve accuracy. Additionally, a comprehensive road user cost (RUC) analysis should be conducted for the alternative routes used during the disruption to better understand the overall economic impact.
2. It is recommended that future research incorporates accident-related costs into the road user cost analysis to provide a more comprehensive understanding of the total economic impact.

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Appendix -1 : Vehicle fleet basic

HDM-4

HIGHWAY DEVELOPMENT & MANAGEMENT

Vehicle Fleet - Basic

Study Name: **Shankar_Thesis**

Run Date: **12-04-2025**

Motorised Vehicle Types:

Name	Base Type	PCSE	No. o Wheel:	No. o Axles	Tyre Type	Tyr Base Recap:	Tyr Retrea Cost (%	Annua Km	Annua Work Hour:	Avg Life	Private Use (%)	Pass enger:	Work Relatec Trips (%	ESALF	Oper Weight (t)	Life Model
Truck- semi- trailer	Articulated Truck	3.00	16	5	Bias ply	3.00	55.00	150,000	6,000	14	0	0.00	0.00	6.80	40.00	Optimal
Light Truck	Light Truck	1.30	6	2	Bias ply	1.30	15.00	30,000	1,300	10	0	1.00	0.00	0.17	6.00	Optimal
Heavy Truck	Heavy Truck	1.60	10	3	Bias ply	1.30	15.00	60,000	2,500	10	0	1.00	0.00	14.00	22.50	Optimal
Tractor	Light Delivery	1.00	6	3	Bias ply	1.30	15.00	15,000	1,300	12	1	1.00	1.00	0.19	8.00	Optimal
Motor Cycle	Motorcycle	0.20	2	2	Bias ply	1.30	15.00	10,000	400	10	100	2.00	5.00	0.00	0.20	Optimal
Three Wheeler	Motorcycle	0.50	3	2	Bias ply	1.30	15.00	15,000	1,200	10	0	5.00	5.00	0.00	0.40	Optimal
Medium Bus	Heavy Bus	1.60	6	2	Bias ply	1.30	15.00	80,000	2,800	12	0	45.00	5.00	0.33	9.50	Optimal
Jeep	Four Wheel Drive	1.00	4	2	Radial ply	1.30	15.00	30,000	750	10	50	3.00	30.00	0.02	1.80	Optimal
Utilities	Light Delivery	1.00	4	2	Radial ply	1.30	15.00	30,000	1,000	12	20	2.00	50.00	0.01	1.50	Optimal
Car	Small Car	1.00	4	2	Radial ply	1.30	15.00	20,000	550	14	50	3.00	30.00	0.00	0.80	Optimal
Small Bus	Light Bus	1.40	6	2	Bias ply	1.30	15.00	50,000	2,400	10	0	28.00	5.00	0.07	6.00	Optimal
Micro Bus	Mini Bus	1.20	4	2	Radial ply	1.30	15.00	50,000	2,400	10	0	10.00	5.00	0.01	2.00	Optimal
Mini Tractor	Light Goods	1.00	4	2	Bias ply	1.30	15.00	12,000	1,300	10	0	0.00	0.00	0.01	2.00	Optimal

Appendix -2 : HDM calibration: Speed flow types

HDM-4
HIGHWAY DEVELOPMENT & MANAGEMENT

Speed Flow Types

Study Name: **Shankar_Thesis**
Run Date: **06-04-2025**

Name	Road Type	Ultimate Capacity (PCSE/lane/hr	Free-flow Capacity (PCSE/lane/hr	Nominal Capacity (PCSE/lane/hr	Jam Speed at Capacity (km/h)	Max Acc Noise amax (m/s/s	Speed Calibration Factor CALBFAC	Speed Multiplication Factor VDESMUL
Four Lane Road	Four Lane Road	1,250	500	1,188	20.00	0.60	1.00	1.00
Intermediate Road	Intermediate Road	1,200	0	840	20.00	0.65	1.00	1.00
Single Lane Road	Single Lane Road	500	0	350	5.00	0.75	1.00	1.00
Two Lane Narrow	Two Lane Road	1,200	120	960	5.00	0.65	1.00	1.00
Two Lane Standard	Two Lane Road	1,200	120	1,080	5.00	0.65	1.00	1.00
Two Lane Wide	Wide Two Lane Road	1,300	195	1,170	5.00	0.60	1.00	1.00
Wide 2 Lane Road	Wide Two Lane Road	1,300	260	1,170	5.00	0.60	1.00	1.00

Appendix -3 : Vehicle Attributes: Economic Cost

Vehicle Class	Unit	Cars		Buses			Trucks			Others			
		Car/Taxi	4x4 Drive Vehicle	Micro-Bus	Mini-Bus	Big Bus	Light Truck	Medium Truck	Heavy Truck	Pick Up Utility	Tractor	Motorcycle	Motorized 3-wheeler
Typical Model		Hyundai i10	SCORPIO S5 4WD (7/8/9 Seater) (Mahindra)	(HIACE)GDH3 22R-EDFDY (TOYOTA)	LCV BUS LP 407/34 4SP-MFIP ABS BS3 (TATA)	MCV BUS LP 1512/42 TC COWL 4X2 BS3 (TATA)	LCV TRUTIP LPT 407/27 HD BB BS3 (TATA)	MCV TRUCK LPT 1615/48 TC CAB BS3 (TATA)	HCV TRUCK CABIN ON LPT 2518/48 TC COWL6X2 ABS BS3 (TATA)	Mahindra Bolero PickUp 2WD P/S 1.5T (Mahindra)	Mahindra Jivo 245 DI 4WD	Honda 125cc	TVS Duramax
HDM-4 Base Type		Car Medium	Four Wheel Drive	Mini-Bus	Mini-Bus	Bus-Medium	Truck-Light	Truck-Medium	Truck-Heavy	Delivey Vehicle Light	Truck-Light	Motor Cycle	Motor Cycle
Market Price	NRs.	4,056,000	5,990,000	9,500,000	2,325,000	3,500,000	2,610,000	3,850,000	5,480,000	2,685,000	1,180,000	286,900	574,900
Market Price	USD	**31,688**	**46,797**	**74,219**	**18,164**	**27,344**	**20,391**	**30,078**	**42,813**	**20,977**	**9219**	**2,241**	**4,491**
Import Duty	-	80%	80%	30%	30%	30%	30%	30%	30%	30%	5%	80%	30%
Excise Duty	-	60%	60%	55%	35%	5%	5%	5%	5%	50%	0%	60%	55%
VAT	-	13%	13%	13%	13%	13%	13%	13%	13%	13%	0%	13%	13%
Road Tax	-	8%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%	7%
Retail/Pretax Price													
Registration Fee	NRs.	800	800	1,500	1,500	2,500	1,500	2,500	2,500	800	800	300	300
Vehicle Ownership Tax	NRs.	23,000	35,500	24,500	24,500	33,000	24,500	33,000	33,000	30,000	23,000	2,800	5,000
Derivation of Economic Cost													
Less Fees													
Less Ownership Tax	NRs.	4,032,200	5,953,700	9,474,000	2,299,000	3,464,500	2,584,000	3,814,500	5,444,500	2,654,200	1,156,200	283,800	569,600
Less VAT	NRs.	3,568,319	5,268,761	8,384,071	2,034,513	3,065,929	2,286,726	3,375,664	4,818,142	2,348,850	1,023,186	251,150	504,071
Less Import Duty	NRs.	1,982,399	2,927,089	6,449,285	1,565,010	2,358,407	1,759,020	2,596,664	3,706,263	1,806,807	974,463	139,528	387,747
Less Excise Duty	NRs.	1,239,000	1,829,431	4,160,829	1,159,267	2,246,102	1,675,257	2,473,014	3,529,774	1,204,538	974,463	87,205	250,159
Less Road Tax (Economic Cost) NRs	**NRs.**	**1,147,222**	**1,709,749**	**3,888,625**	**1,083,427**	**2,099,161**	**1,565,661**	**2,311,228**	**3,298,854**	**1,125,737**	**910,713**	**87,205**	**233,794**