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# Determination of Passenger Car Unit and Capacity at Grades of Two Lane Undivided Highway: A Case Study of Khurkot–Dhulikhel Section of BP Highway

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**Abstract**

The majority of Nepal's National Highway and feeder road system comprises two-lane highways with heterogeneous traffic conditions. The passenger car unit (PCU) and roadway capacity can be influenced by the factors such as lane width, gradient, lateral clearance, and shoulder conditions. Recognizing that grade magnitude (%) is an important yet unexplored roadway factor in Nepal, the present study primarily aims to estimate passenger car unit on two-lane undivided hilly roads with gradients under prevailing heterogonous traffic conditions.

This study aims to determine the PCU values and roadway capacity at grade under mixed nature traffic flow for two-lane undivided highway. In this research, the necessary data were collected at five sections of BP highways using a digital video recorder, which was then analysed to assess traffic characteristics and calculate PCU values. Using the PCU values, the road capacity was estimated using Greenshield's model. For capacity estimation flow and density were addressed by using dynamic PCU values.

This study reveals that the PCU of all categorized vehicles increases linearly with the increase in gradient while roadway capacity decreases with increase in grade. It was observed that PCU values obtained for two-wheelers in all sections are smaller than the PCU values specified in NRS 2013, whereas for buses, trucks, LCVs they are higher than the PCUs given in NRS 2013. The study highlights the impact of road grade on the PCU for different vehicle categories on a highway. Additionally, the study demonstrates that the developed capacity values are realistic and consistent with the values presented in the Highway Capacity Manual (HCM) of developing countries such as Indonesia and China. These results are expected to be beneficial for practitioners and the ongoing effort to develop a highway capacity manual.

*Keywords*: Traffic composition, Speed, Passenger Car Units, Volume, PCU, and Capacity

## 1. Introduction

In Nepal, majority of the highway system consists of two-lane roads. The geographical and topographical features in Nepal show that a large area of land is covered by hills and mountains across the country. Connectivity for people in hilly terrain to other parts of the country is a significant issue concerning to planning, designing, and operation of hilly roads. Nepalese traffic conditions consist of diverse vehicle categories with different static and dynamic characteristics, making it a heterogeneous flow. The vehicles' dynamic and complex behavior can be dealt with by converting them into an equivalent passenger car unit (PCU).

Highway capacity refers to the maximum number of vehicles a roadway or transportation facility can handle efficiently and safely under specific traffic conditions. It is critical measure used in transportation engineering and planning to assess the performance of roadway and design transportation systems. It is generally measured in passenger car units (PCU) per hour.



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In Nepal, majority of roads pass through hilly terrain with significant grades or slopes. The grade of road can have a notable impact on the passenger car unit (PCU) and the capacity of a road. So, this study intended to determine the effect of road grade on PCU and capacity of hilly roads.

Minimal research has been done in Nepal on traffic flow characteristics on hilly roads; hence, it motivates establishing suitable roadway capacity-related guidelines using fundamental traffic flow diagrams for roads with different grades in rolling and hilly terrains.

### *1.1. Research questions*

- What are the PCU values for different vehicle categories on selected road sections with varying grades?
- What is the relationship between PCU and grade of the road?
- What is the relationship between the flow characteristics of traffic and what is the capacity of road at different grades of selected section?
- What is the relationship between road capacity and road grade?

### *1.2. Research objectives*

The general objective of this study is to determine the PCU values and the capacity of road at different grades of two-lane undivided carriageway of BP National Highway in Nepal.

- To determine the PCU value of different vehicle categories at different grades of selected road sections.
- To establish the relationship between PCU and grades of roads.
- To determine the relationship between traffic flow, traffic density, and mean stream speed of the road section and to determine capacity of road at different grades of selected sections using proposed PCU.
- To establish the relationshipaa between road capacity and road grade.

## 2. Literature review

### *2.1. Introduction PCU and Roadway capacity*

Traffic flow is generally heterogeneous. However, the degree of heterogeneity varies with the context. For example, it is usually more for developing countries. Due to this heterogeneity, traffic studies often become critical. Passenger car unit (PCU) is used to convert the heterogeneous traffic volume into its equivalent homogeneous.

Passenger car unit of a vehicle type is defined as 'the measure of relative interaction between a vehicle and a traffic stream concerning for a standard passenger car under a specified set of roadway and traffic conditions' (CSIR, 2017).

Different types of vehicles take up differing amounts of road space, have different speeds (for geometric design), and impose differing loads on the road structure (for structural design). It is, therefore necessary to adopt a standard traffic unit to which other types of vehicles may be related. For geometry design of roads this standard is the 'Passenger Car Unit (PCU)' which is that of a standard car (passenger car), light van or pick-up. Other types of vehicles are taken into account by multiplying by the equivalency factors (NRS 2013). The highway capacity Manual (2010) defined the capacity as the maximum howdy rate at which pedestrian or vehicle can be reasonably expected to traverse a point or a uniform segment of a lane or roadway during a given period of time, under prevailing roadway, traffic, and control conditions.

Chandra (2004) studied the effect of influencing parameters like gradient, lane width, shoulder width, traffic composition, directional split, slow moving vehicles, and pavement surface conditions on capacity of two-lane road under mixed traffic conditions is evaluated and adjustment factors for each condition are proposed. Highway capacity manual (2000) states that the capacity of a two-Lane rural highway under ideal conditions is 3200 PCU for both directions combined. The ideal condition given in the manual does not include the riding quality of a road which deteriorates with time.

Nepal road standard (2013) has adopted PCU values representing standard car (passenger car), light van or pick-up by stating that “different types of vehicles take up differing amounts of road space and have different speeds (for geometric design) and impose differing loads on the road structure (or structural design)”.

Table 1. Vehicle types and PCU according to NRS (2013)

| S.N | Vehicle Type | Equivalency factor |
|---|---|---|
| 1 | Bicycle, Motorcycle | 0.5 |
| 2 | Car, Auto Rickshaw, SUV, Light Van and Pick Up | 1 |
| 3 | Light (Mini) Truck, Tractor, Rickshaw | 1.5 |
| 4 | Truck, Bus, Minibus, Tractor with trailer | 3 |
| 5 | Non-motorized carts | 6 |

### *2.2. PCU Determination*

In the past, various techniques have been adopted to estimate PCU of vehicles. Werner and Morall (1976) proposed utilizing a headway ratio method to determine PCU values at low levels of service. Aerde and Yagar (1984) used the speed parameter to estimate the PCU of trucks, recreational vehicles, and other vehicles on a two-lane highway. Thorne (1965) employed regression analysis technique to find PCU of the bus. Craus et al. (1980) proposed an alternative method for calculating the PCU of trucks on a two-lane highway, taking into account the real delay caused by trucks and oncoming traffic. Elefteriadou et al. (1997) used a simulation technique with speed as the performance measure.

Bomzon et al (2021) studied mixed traffic conditions to determine PCU values along the hilly road of east Sikkim, found that the traffic condition has less or no influence in the PCU value when speed area method is used to estimate PCU values. As there is no guidance in India for calculation of traffic capacity for hill roads, therefore this study provides an insight to traffic capacity determination for hilly terrain, the speed area method is found to be more suitable for determination of PCU.

Biswas (2021) examined the methods adopted for estimating PCU and evaluated the advantages and limitations of each approach. Passenger Car Unit (PCU) serves as a comparative weighting factor assigned to different vehicle categories' traffic volumes to address the diversity in mixed traffic scenarios. Numerous studies have been conducted to estimate PCUs for various vehicle categories. Some researchers have proposed fixed PCU values, while others have recognized the dynamic nature of PCUs. These studies have also explored how PCUs vary with factors such as traffic characteristics and road geometry. The review reveals that PCUs recommended in the literature are often tailored to specific regions due to variations in traffic patterns and driving norms among nations, leading to significant inconsistencies in outcomes. These disparities not only exist in the range of PCUs but also in how they fluctuate with different influencing factors. This study offers a comprehensive overview of research findings regarding PCU estimation on urban roads.

Tullu et al. (2016) in their study provided that PCUs of different type of vehicles found on urban roads in Quetta at different volume-capacity (v/c) ratios. Traffic simulation software VISSIM is used to generate traffic flow and vehicle speeds under different conditions. A network model is created in VISSIM to replicate field conditions of study area and important VISSIM parameters are adjusted to reflect heterogeneous traffic conditions of study area which is further validated with field data. The study found out that PCU of different type of vehicles is dynamic in nature, and changes with the change in traffic volume and vehicle proportion.

Mohan (2010) studied the effect of gradient on stream equivalency factor for undivided two-lane highways. To develop stream equivalency factor for undivided two lane highways with the main focus in its effect on varying gradient. The result from four sites a model for predicting SEF values were developed and the same was found valid for the fifth site.

### *2.3. Effect of Roadway and Traffic parameters on PCU*

Emer et al. (2021) initiated the study to establish the PCU values that cater to the local setting. This study was focused to estimate the PCU values of multilane highway in Addis Ababa city and determining the influence of traffic volume and width of road on the value of PCU. In this study, dynamic PCU method was adopted to determine the PCU values and linear regression analysis was performed for model development. The study result indicates that as the traffic volume and carriageway width increase, the PCU value also increases. It was also found that PCU values showed higher than those provided by highway capacity manual (HCM). Hence the PCU values obtained are reflecting the existing condition in the locality.

Khadka (2013) studied the effect of road width on passenger car units of vehicles under heterogeneous traffic conditions, in this study, the PCU values on the highways are determined by using relation given by Chandra & Kumar (2003). The PCU is directly proportional to the ratio of clearing speed of the vehicle and inversely proportional to the space occupancy ratio of the vehicle concerning the standard Area of the vehicle i.e., car. The PCU of a vehicle type is taken as given by Chandra and Kumar (2003). The vehicles are divided into five categories: BUS, Truck, LCV, Car, and Two-wheelers. It was found that the relationship between PCU and carriageway width is linear.

Shrestha (2013) developed saturation flow and delay models for signalized intersection in Kathmandu used multiple regression analysis to determine PCU values. The vehicles were divided into six categories: Car, Bus, Truck, Microbus, Two-Wheeler, and Tempos. The study found PCU values of particular vehicle types are not constant for all the intersections. This finding re-established the fact that unified passenger car unit concept for different vehicles do not always hold good for non-lane traffic-based condition.

Chandra and Kumar (1996) used speed and area-based concept to calculate the passenger car unit PCU of various vehicle types under mixed traffic conditions. Their method considered both the area and speed of vehicles, rather than only focusing on vehicle length. Information was gathered from ten segments of two-lane roads located across various regions of India. The carriageway width, which refers to the total paved surface width of a road excluding its shoulders, ranged from 5.5 to 8.8 meters. Vehicles were classified into nine distinct categories, and their respective PCUs were calculated at each road segment. The PCU values for different types of vehicle calculated at different sections showed the linear variation in PCU for different types of vehicles with lane width at different sections. It was found that the PCU for a vehicle type increases linearly with the width of carriageway. The relationship between PCU and the Carriageway width is given below in Table 2.2. This is attributed to the more significant freedom of movement on wider roads and therefore a greater speed differential between a car and a vehicle type.

Ghosh et al. (2016) illustrated the dynamic nature of PCU factors on two-lane intercity highways under highly heterogeneous traffic composition. They derived PCU based on the speed and size of vehicle type in the traffic stream relative to the standard passenger car. By formulating simultaneous equations to calculate vehicle speeds for different traffic compositions and volumes, they determined PCU factors. While numerous plots were used to depict the impact of traffic composition and volume on PCUs, they proposed the concept of a stream equivalency factor to convert heterogeneous traffic streams into homogeneous ones comprised solely of passenger cars. A simple linear equation is developed using data from three sites to calculate this factor for a known traffic volume and proportional composition of a traffic stream. Field data from a fourth site are used to validate the proposed model. The proposed mode simplifies PCU estimation for various vehicle types on two-lane intercity highways, streaming the process and eliminating the need for individual PCU factor calculations.

### *2.4. Roadway Capacity estimation*

Pal. Jain, (2019) realized that the grade magnitude (%) is one of the critical factors, which affect the PCU and road capacity in India. This study aims at estimating capacity on two-lane undivided hilly roads under heterogeneous traffic conditions. To estimate the capacity of road at gradient four different road sections with varying magnitude of gradient (2% to 7%) were selected. In this study; analysis for capacity estimation was done by using fundamental diagram described by Greenshield's traffic flow theory. Dynamic PCU value and 5- minute traffic flow in PCU/hr were considered for capacity estimation. It was found that the capacity of two-lane roads decreases with increase in magnitude of gradient (%). Simple linear relationship was existed between magnitude of gradient and capacity that is, Capacity = 3040.7 - 180.94×Gradient, with $R^2$ value 0.96. K.P et al. (2017) studied the effect of gradient on PCU and capacity factor for undivided two-lane national highway. This study concern to determine the PCU values of vehicles under mixed traffic flow condition at congested highway. An intension of this work is to analyze capacity of two-lane undivided highway in heterogeneous traffic condition using Chandra's method. The PCU values of different types of vehicles are given in Table 2. The relationship between capacity and gradient obtained are as: Capacity = 256.25 ×Lane width - 107.75; for ascending grade & Capacity = 910.42 ×Lane width - 2547.6; for descending grade. The capacity based on grade % is given as: Capacity = 15.209 × Gradient + 776.89; for ascending grade and Capacity = 57.689 × Gradient + 583.85; for descending grade.

Table 2. The PCU values of different types of vehicles

| S.N | Gradient (%) | PCU | | | | |
|---|---|---|---|---|---|---|
| | | Car | Bus | 2W | LCV | HCV |
| 1 | +5.88 | 1 | 6.59 | 0.25 | 3.50 | 5.72 |
| 2 | +2.5 | 1 | 6.49 | 0.24 | 3.45 | 5.42 |
| 3 | +1.11 | 1 | 5.74 | 0.23 | 3.40 | 5.16 |
| 4 | -1.11 | 1 | 5.48 | 0.192 | 3.05 | 5.42 |
| 5 | -2.5 | 1 | 4.80 | 0.190 | 2.98 | 5.13 |
| 6 | -5.88 | 1 | 4.72 | 0.188 | 2.97 | 5.09 |

Khode (2009) studied impact of lane width of road on passenger car unit capacity under mix traffic conditions in cities on congested highways. The objective is to estimate the value of PCUs for mixed traffic condition of moving vehicles in the traffic flow. The capacity of a 7.2 m wide road in PCU values is estimate 3348.48 PCU/hr which is larger than the value of 3,200 PCU/h suggested in HCM 2000.

Chandra (2004) suggested that the procedure for capacity estimation of a two-lane road. The base capacity of two-lane road for Indian condition was reported as 3100 PCU/hr. In this study, gradient up to 4% are considered. Moreover, adjustment factors are derived for gradient, as every 1% upgrade decreases the capacity by 2.60 %, and 1% downgrade increases the capacity by 3 %. IRC: 64-1990 provides some guidelines for the capacity of two-lane roads; however, these guidelines provide very little information about the capacity values of roads having grades of significant magnitudes.

### *2.5. Fundamental relationships of traffic flow*

The fundamental relations of traffic flow refer to the relationship between the three critical elements of traffic flow: speed, volume, and density.

***Speed***

According to the HCM (2000), Speed is defined as the rate of motion expressed in terms of the distance travelled in one unit of time, typically expressed in kilometer per hour (km/hr). If n vehicles travel a segment of length L with travel time t1, t2, ……, tn, the average travel speed is given as:

$$V_s = \frac{nL}{\sum_{i=1}^{n} t_i}$$

(Equation1)

$$V_t = \frac{\sum_{i=1}^{n} V_i}{n}$$

(Equation 2)

Where,
$V_s$ = Average travel speed or space mean speed (m/sec)
$V_t$ = Time mean speed or spot speed (m/sec)
$V_i$ = Mean speed for type i vehicle (km/hr)
L = length of the roadway segment (m)
n = Observed number of vehicles

***Volume***

Volume refers to the total number of vehicles traversing a specific point or segmrnt of a roadway within a given amount of time. According to HCM (2000), PHF is defined as the ratio of total hourly volume to peak flow per hour, represented by the Equation (3):

$$PHF = \frac{Hourly\ volume}{Peak\ Flow\ rate}$$ (Equation 3)

If 15-minute periods are used, then

$$PHF = \frac{V}{4 \times V_{15}}$$ (Equation 4)

When PHF is known, $v = \frac{V}{PHF}$ (Equation 5)

where,
PHF = Peak-hour factor
V = Peak-hour volume (vehicles/hr)
$V_{15}$ = Volume during the peak 15-minute for the peak hour (vehicles/15min)
v = Flow rate for a peak 15-minute period (vehicles/hr)

***Density/Concentration***

It is defined as the number of vehicles occupying a specific lane or stretch of road, and is typically stated in terms of vehicles per km (veh/km). Estimation of density in the field directly is challenging, but it can be achieved through aerial photography, videography, or 17 viewing substantial sections of highway, but it is more typically derived from an equation if the speed and rate of flow are known.

$$q = v \times k$$ (Equation 6)

where,
q = rate of flow (vehicles/hr),
v = average travel speed (km/hr)
k = average density (vehicle/km)

***2.6. Greenshild's Model***

Greenshield postulated that in uninterrupted flow conditions, there exist a linear relationship between speed and density. This relationship is expressed mathematically as:

$$V = A - B \times k$$ (Equation 7)

Where v = speed (miles/hour, kilometres/ hour)
A, B = constants determined from field observations
k = density (vehicles/mile, vehicles/ kilometer)

In Greenshield's model, the constants 'A' and 'B' typically derived from field observations. This involves collecting velocity and density data in the field, plotting the data, and using linear regression to fit a line through the data points. 'A' represents the free flow speed, while 'A/B' represents the jam density.

Integrating Greenshield's speed-density relationship into the general speed-flow-density relationship yields the following expressions:

$q = (A - B \times k) \times k$ or $q = A \times k - B \times k^2$ (Equation 8)

where:

$q$ =flow (vehicles/hour)

A,B = constants

$k$ = density (vehicles/mile, vehicles/km)

This new relationship between flow and density provides an avenue for finding the density at which the flow is maximized.

$dq/dK = A - 2B \times K$

Setting, $dq/dK = 0$ yields: $K = A/(2 \times B)$

Hence, at the provided density, the flow will be maximized. Inserting this maximized value of 'K' into the original speed-density relationship yields the speed at which the flow is maximized.

$V = A - B \times (A/(2 \times B))$ or, $V = A/2$

This suggests that the maximum flow occurs when traffic flows at half of the free-flow speed (A). Inserting the optimum speed and density into the speed-flow-density relationship yields the maximum flow.

$q = (A/2) \times \{A/(2B)\}$ or $q = A^2/(4 \times B)$ (Equation 9)

As the density increases, the flow initially rises to a maximum value, but further density increments lead to a decrease in flow until reaching jam density, resulting in zero flow condition.

## 3. Methodology

### *3.1. Research approach*

This research was conducted by field visit, and Video Observation methods to calculate the PCU and capacity of road sections at grades. This chapter discusses in details the methodology of the Study and includes following steps.

### *3.2. Study area*

Table 3. Measurement of roadway element

| Name of section | Section number | Chainage (0+000 at Khurkot) | Grade (%) | Length of stretch(m) | Width of Carriageway(m) |
|---|---|---|---|---|---|
| Khurkot | HS 1 | 2+250- 2+290 | 2.1 | 40 | 6.8 |
| Kutunje | HS 2 | 55+610- 55+650 | 3.2 | 40 | 6.75 |
| Dhulikhel | HS 3 | 82+030- 82+075 | 4.3 | 45 | 6.75 |
| Mulkot | HS 4 | 17+076- 17+111 | 5.5 | 35 | 6.8 |
| Nepalthok | HS 5 | 31+250- 31+295 | 6.8 | 45 | 6.78 |

The study was carried conducted on the Khurkot-Dhulikhel section of BP Highway (H06) located in Sindhuli and Kavreplanchok District of Nepal. According to department of road (DoR, 2022), around 13,000 vehicles travel through the highway daily. The total length of road section is 85.7 Km with two lane undivided carriageway. The details of study stretches are explained in Table 3 and Figure 2 shows the site locations and their respective trap lengths considered for speed estimation. Total five hours of video recording was done with the help of video cameras for each of the selected road sections.

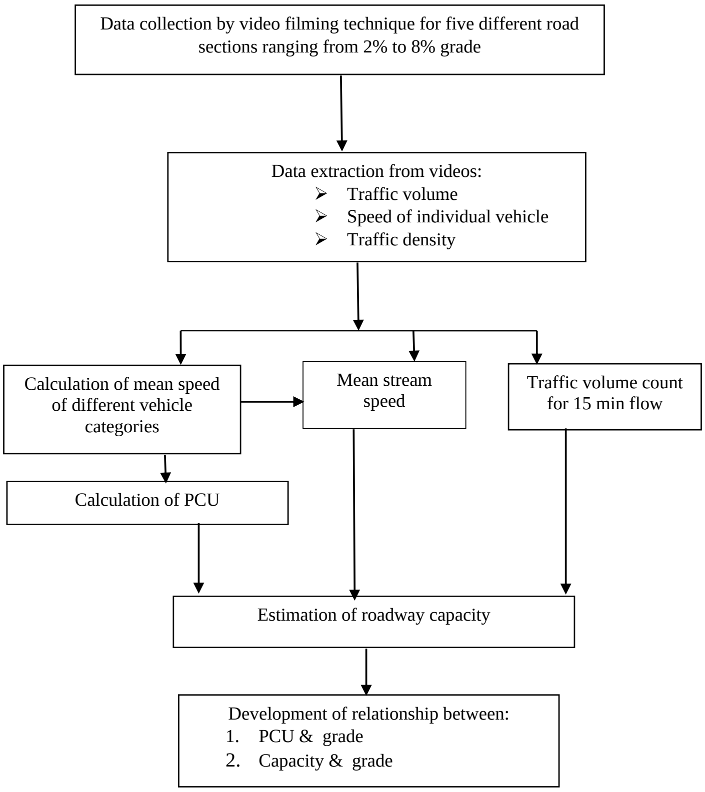


Figure 1. Conceptual Framework for Research Study

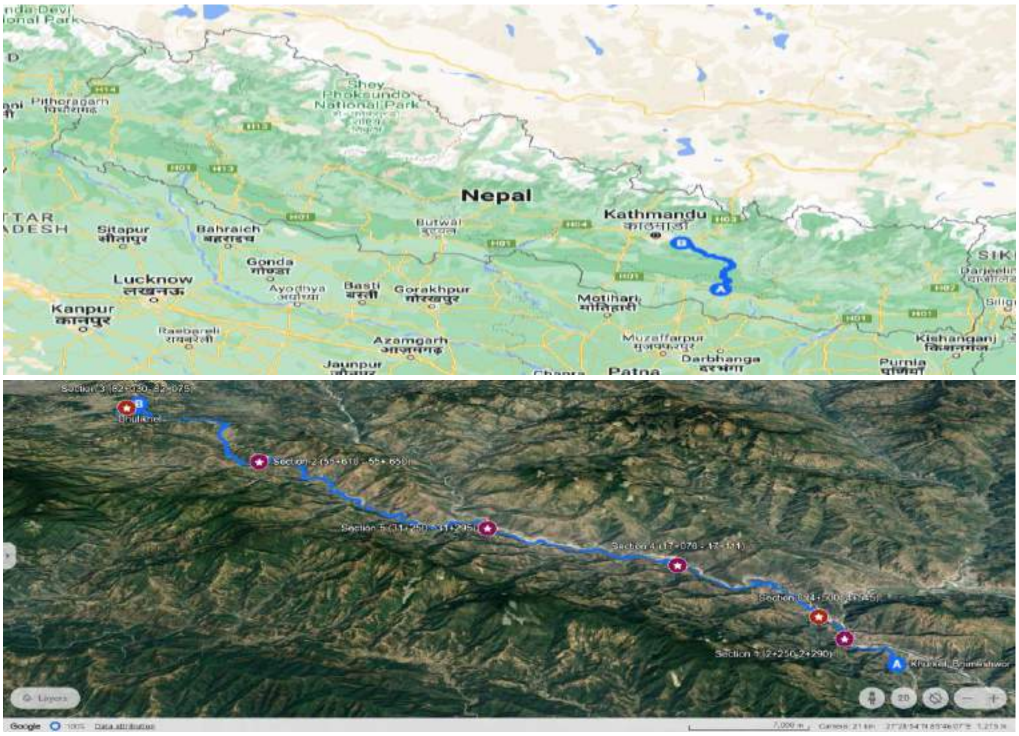


Figure 2. Study area location (source: Google map)

### *3.3. Data collection and Extraction*

#### *3.3.1. Vehicle dimension*

The dimension of vehicles in Nepal was surveyed by Nepal automobile survey (2016), the data from this survey and field measurement of vehicles was used for the study.

Table 4. Vehicle Categories and their Dimension

| Vehicle Category | Vehicles Included | Average Vehicle Dimension | | Projected Area on Ground ($m^2$) |
|---|---|---|---|---|
| | | Length (m) | Width (m) | |
| Bus | Buses | 11.12 | 2.49 | 27.74 |
| Truck | Truck | 7.5 | 2.35 | 17.62 |
| LCV | Minibus, mini truck, micro bus | 6.10 | 2.10 | 12.81 |
| Cars | Car, jeep, van | 3.74 | 1.44 | 5.39 |
| Two-wheeler | Scooters, bikes | 1.87 | 0.64 | 1.2 |

*(Source Nepal automobile survey, 2016)*

#### *3.3.2. Traffic distribution*

Analysis of traffic composition gives the idea for the proportion of wide variety of vehicles. The study shows that two-wheeler i.e. Motor cycles have the highest percentage in the traffic stream and truck has the lowest percentage in the traffic stream and percentage of car shows slightly variation in volume of traffic. All these traffic distributions at different sections are presented Figure 3.

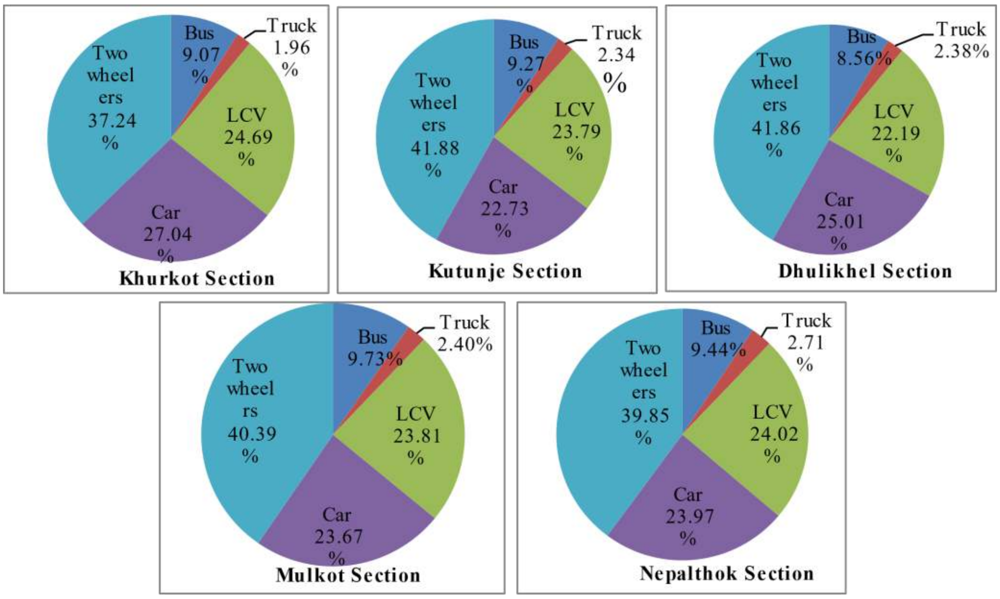


Figure 3. Traffic distribution at selected sections

#### *3.3.3. Speed data*

The speed of each vehicle of all categories was calculated by using travel time and length of stretch. The spot speed is usually measured by measuring time taken by vehicle to traverse a fixed distance less than 90m (Mathew, 2019). The PCU factor is based on the mean speed values of different vehicle classes. This is calculated by dividing the mean speed value of passenger cars by the mean speed value of any vehicle class. Therefore, a longitudinal stretch with trap length, as given in Table 3 was made on the carriageway of each section to measure the vehicle speed. The video was recorded and recorded film was played on a large screen , and the data was extracted. The average time taken by each vehicle type to travel the trap length was measured by the time displayed on the screen with an accuracy of 0.1 s with the help of stopwatch. This time was used to calculate the speed of a vehicle passing through the section. The average speed of different vehicle categories at different sections of highway is presented in Table 5.

Table 5. Space mean Speed distribution of different vehicles at different gradient

| S.N | Grade (%) | Speed distribution of different vehicles (km/hr) | | | | |
|---|---|---|---|---|---|---|
| | | Bus | Truck | LCV | Car | Two-Wheeler |
| 1 | +6.8 | 36.91 | 30.16 | 34.35 | 40.46 | 41.33 |
| 2 | +5.5 | 40.23 | 34.58 | 37.4 | 44.02 | 44.8 |
| 3 | +4.3 | 43.63 | 38.07 | 40.03 | 47.47 | 47.81 |
| 4 | +3.2 | 48.29 | 42.62 | 44.12 | 52.27 | 52.47 |
| 5 | +2.1 | 52.92 | 46.56 | 48.89 | 56.93 | 56.98 |
| 6 | -2.1 | 55.99 | 52.38 | 54.18 | 60.53 | 58.12 |
| 7 | -3.2 | 57.94 | 54.59 | 56.06 | 62.25 | 59.54 |
| 8 | -4.3 | 59.69 | 56.49 | 58.05 | 63.85 | 60.91 |
| 9 | -5.5 | 61.99 | 58.9 | 59.89 | 65.79 | 62.73 |
| 10 | -6.8 | 62.87 | 59.92 | 61.18 | 67.17 | 63.61 |

Speed observation was taken to account for vehicles moving freely without any congestion. Referring Table 5, the average speed of motorized two-wheelers (motorcycles) found to be lower than the average speed of car for downgrade. At higher density the speed of two wheelers is greater than the speed of car for ascending grade and at lower density the speed of two wheelers is less than that of car for descending grade.

### *3.3.4. Follow Data:*

The general practice to quantify the heterogeneous traffic is to convert the flow rate into PCU/hr. As per HCM (2010), 15-min interval volume is considered to express flow rate on level roads. This type of suitable interval is not given in HCM (2010) for hilly roads or roads passing through rolling/hilly terrains. Under Nepalese conditions also, suitable time interval to be considered for developing speed flow diagram and expressing capacity has not been yet studied on roads having significant grades. Thus, in this study, flow rates expressed in PCU/hr are analysed for 15-min interval along with other relevant macroscopic variables such as vehicle speeds and traffic density.

### *3.3.5. Density data*

Obtaining density values every second proved to be a laborious and challenging task. As a more practical approach, density values were acquired at specific interval. The video playback was paused at the end of each 30 seconds, allowing for a count of different vehicle typesss in the area during that brief interval. The densities extracted within each 15- minute segment were then averaged to determine the overall density for each 15-minute period.

## *3.4 Data analysis*

### *3.4.1 Data analysis for PCU*

This study adopted a dynamic PCU method for PCU estimation. The reason for using dynamic PCU method is due to the non-lane based traffic movement of vehicles and due to higher heterogeneity of traffic in Nepal. In conditions when vehicles do not follow lanes strictly, the occupancy is better reflected by area (Chandra 2003). Speed area method provides an insight to traffic capacity determination for hilly terrain; this method is more suitable for determination of PCU (Bomzon et al., 2021). The PCU of all vehicle categories was calculated by using Chandra’s method of PCU estimation.

$$PCU = \frac{V_c/V_i}{A_c/A_i}$$ (Equation 10)

where; Vc = mean speed of a car and Vi = mean speed of vehicle type i,
Ac = projected area of the car, and Ai = projected area of vehicle type i.

### *3.4.2 Data analysis for capacity*

Under uninterrupted and heterogeneous traffic environment speed- density model is linear in nature (Gautam & Jain, 2018). So in this study, relation between speed and flow was plotted from observed field data and Greenshield's assumption of linear speed-density relationship was considered. Subsequently, the data points obtained from speed-density equation shall be used to derive speed-flow diagram to obtain the capacity of road. The road capacity was equal to the maximum flow obtained from the speed-flow relation. The fundamental diagram method is used for the estimation of capacity, which is based on the primary traffic flow equation between the three variable speed (v), flow (Q), and density (k).

It is expressed as: $Q = K \times V$ (Equation 11)

where, Q=Flow (PCU/hr); K=Density (PCU/km); V=Stream Speed (Km/hr)

### *3.4.3 Analysis of the relationship between PCU and grade*

Calculated PCU value and grade (%) of road for each type of vehicle are plotted in the graph for graphical representation. Then the coefficient of determination, $R^2$, is employed to assess the extent to which variations in one variable can be elucidated by variances in another variable.

### *3.4.3 Analysis of the relationship between capacity and grade*

Road grade (%) and corresponding estimated capacity value of each type of vehicle are plotted in the graph for graphical representation. Then the coefficient of determination, $R^2$, helps to analyse how differences in one variable can be explained by a difference in a second variable.

### *3.5 Model validation*

To validate PCU estimation models for road upgrades and downgrades. One hour of video data was captured during daytime (10:30 a.m. to 11:30 a.m.) on a road section with a 7.9 % grade. The validation process was conducted by comparing observed and estimated PCU measurements. For validation of various PCU at upgrade and downgrade the t-statistical test was used. The standard t-distribution table was used to estimate the t-statistics, p value, and t-critical values at 95% confidence level.

## 4. Result and discussion

### *4.1 PCU calculation*

The PCU values for different categories of vehicles calculated at different sections of highways are presented in Table 6. This shows the variation in PCU for different types of vehicles with grade of road at different sections. The PCU factor is based on the mean speed values and projected area of different vehicle classes. The PCU value of vehicle of (i) type was calculated using Chandra equation. The PCU calculation of each vehicle categories at all sections is given in the Appendix C.

Table 6 shows the calculated PCU values at selected section having different grade. The PCU values for bus is found to be maximum followed by truck, LCV, car, and two-wheelers at all grades (%). The study shows that the speed area ratio of truck is more than that of bus, which cause the PCU of trucks is less than that of bus. The calculated PCU values in this study are different from values given by NRS 2013.

Table 6. PCU values for different categories of vehicles at different sections

| S.N | Grade (%) | Passenger Car Unit (PCU) | | | | |
|---|---|---|---|---|---|---|
| | | Bus | Truck | LCV | Two Wheeler | Car |
| 1 | +6.8 | 5.7629 | 4.4797 | 2.8596 | 0.2274 | 1 |
| 2 | +5.5 | 5.7312 | 4.2352 | 2.8469 | 0.2266 | 1 |
| 3 | +4.3 | 5.6396 | 4.1054 | 2.8385 | 0.2242 | 1 |
| 4 | +3.2 | 5.5921 | 4.0245 | 2.8264 | 0.2235 | 1 |
| 5 | +2.1 | 5.5414 | 4.0006 | 2.7699 | 0.2228 | 1 |
| 6 | -2.1 | 5.3424 | 3.6272 | 2.5495 | 0.2138 | 1 |
| 7 | -3.2 | 5.2887 | 3.5654 | 2.5242 | 0.2129 | 1 |
| 8 | -4.3 | 5.2518 | 3.5248 | 2.4937 | 0.2124 | 1 |
| 9 | -5.5 | 5.2080 | 3.4816 | 2.4893 | 0.2123 | 1 |
| 10 | -6.8 | 5.2071 | 3.4703 | 2.4710 | 0.2108 | 1 |

### *4.2 Relationship between PCU and grade*

The relationship between PCU and grade of road is established using the data from first five sections at upgrade and downgrade and a next grade is taken for validation of relationship. The analysis carried out showing the effect of road grade on the PCU values of different vehicles, resulting in development of linear relationship between PCU and grade of road. In the following sections the relationship between PCU with ascending grade and descending grade are presented.

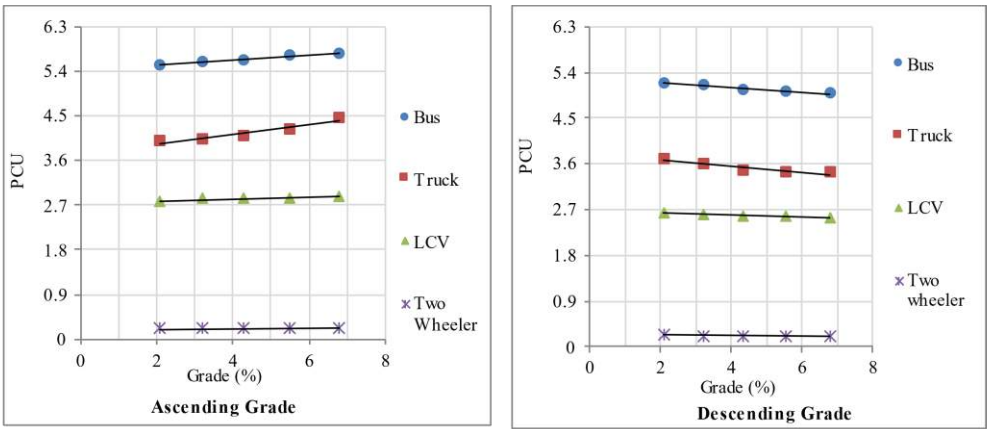


Figure 4. Relationship between PCU and grade (%)

### *4.5 Summary of PCU and grade relationship*

Table 7. Summary of relationship of PCU of different types of vehicles with road-grade

| Vehicle type | Direction | Relation between passenger car unit and road grade (G) | $R^2$ value |
|---|---|---|---|
| Bus | Upgrade | PCU=0.0497G + 5.4359 | 0.979 |
| | Downgrade | PCU= -0.0297G + 5.3897 | 0.918 |
| Truck | Upgrade | PCU=0.1011G + 3.7264 | 0.908 |
| | Downgrade | PCU= -0.0337G + 3.6814 | 0.938 |
| LCV | Upgrade | PCU=0.0169G + 2.7544 | 0.804 |
| | Downgrade | PCU= -0.0163G+2.5767 | 0.936 |
| Two wheeler | Upgrade | PCU=0.0011G + 0.2203 | 0.953 |
| | Downgrade | PCU= -0.0006G + 0.2149 | 0.931 |

The overall summary of relationship of PCU of different types of vehicles with grade of road and its respective $R^2$ Value are presented in Table 7.

### *4.6 Validation of PCU model*

A mathematical model must be validated for its acceptance. The selection of the validation techniques is crucial. If the data collected are from discrete experimental units, statistical analysis is appropriate. In this case mathematical models are generated using the data collected at five sections having grades 2.1%, 3.2%, 4.3%, 5.5%, and 6.8%, while for the validation of models one more section having 7.9% grade is chosen. These data sets are independent. Thus, a two-tailed t-test is used for model validation (Aman and Parti, 2021). The observed PCU values of all the vehicle categories are determined from the collected data at 7.9% grade. The measurement of road elements for validation of PCU models is listed in Table 8. Further the PCU values are also estimated from proposed models. These observed values and model values are then compared statistically for their statistical significance. The t test approximates the exact discrepancy among two groups using the ratio of the difference in group means over collective standard error of both the groups. A level of significance of 5% is adopted for the study. The result of these test are summarized in Table 9 and Table 10. The observed and model values of PCU of all category vehicles for upgrade and downgrade are listed in Appendix D.

Table 8. Measurement of Road elements of section for validation of PCU models

| S.N. | Grade of road (%) | Length of stretch(m) | Width of Carriageway(m) | Shoulder |
|---|---|---|---|---|
| 1 | 7.9 | 35 | 6.69 | 0.3 m Paved |

To validate the proposed model of PCU at the grades was done by assuming two hypotheses, they are;
Null Hypotheses (H0): The difference between actual and predicted PCU equals zero. i.e. H0: $\mu 1 = \mu 2$.
Alternative hypothesis (Ha): The difference between actual and predicted speed is not equal to zero. i.e. Ha: $\mu 1 \neq \mu 2$.

Table 9. t-test between actual and predicted PCU for Upgrade

| S.N | Vehicle type | Mean value | | $t_{0.05}$ | $t_{critical}$ | P -value | comment |
|---|---|---|---|---|---|---|---|
| | | Observed | Model | | | | |
| 1 | Bus | 5.787 | 5.829 | -0.8329 | 2.57058 | 0.4689 | H0 is true |
| 2 | Truck | 4.516 | 4.525 | -0.0819 | 2.57058 | 0.4137 | H0 is true |
| 3 | LCV | 2.914 | 2.888 | 0.5724 | 2.57058 | 0.5917 | H0 is true |
| 4 | Two wheelers | 0.228 | 0.229 | -1.644 | 2.5705 | 0.1610 | H0 is true |

Table 10. t-test between actual and predicted PCU for downgrade

| S.N | Vehicle type | Mean value | | $t_{0.05}$ | $t_{critical}$ | P -value | comment |
|---|---|---|---|---|---|---|---|
| | | Observed | Model | | | | |
| 1 | Bus | 5.190 | 5.155 | 0.69352 | 2.5705 | 0.5188 | H0 is true |
| 2 | Truck | 3.425 | 3.415 | 0.28893 | 2.5705 | 0.7842 | H0 is true |
| 3 | LCV | 2.442 | 2.448 | -0.2642 | 2.5705 | 0.8021 | H0 is true |
| 4 | Two-wheelers | 0.210 | 0.210 | 1.2533 | 2.5705 | 0.2655 | H0 is true |

Here, t- statistic is lower than the critical-t value, and P-value exceeds the level of significance (i.e. P value >0.05). So, it failed to reject null hypothesis, i.e. the mean difference between actual and predicted PCU value is zero. Hence, proposed models of PCU estimation were validated for field data.

### *4.7 Capacity estimation and flow characteristics*

As per the methodology discussed, the relationship between speed and density is established based on the field data points and the Speed-flow diagrams are developed by using linear relationship between speed and density (Greenshield's model). The average values of upgrade and downgrade PCU and that of speed was considered to calculate the flow and mean stream speed for each section. The average speed and average PCU of both directions are shown in Table 11. Capacity (PCU/hr) is measured as the maximum flow in speed-flow diagram or the flow at optimal density from flow density relationship. It is found that the capacity value of roadway decreases with increase in the gradient. The capacity of all five sections was calculated by using 15-minute flow rate. The flow, density and speed of the vehicles listed in the Appendix E.

Table 11. Average speed and PCU of upgrade and downgrade direction

| Grade (%) | Bus | | Truck | | LCV | | Two wheeler | | Car | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Speed | PCU | Speed | PCU | Speed | PCU | Speed | PCU | Speed | PCU |
| 2.1 | 54.45 | 5.441 | 49.47 | 3.813 | 51.53 | 2.659 | 57.55 | 0.2183 | 58.73 | 1 |
| 3.2 | 53.11 | 5.440 | 48.60 | 3.794 | 50.09 | 2.675 | 56.00 | 0.2182 | 57.26 | 1 |
| 4.3 | 51.66 | 5.445 | 47.28 | 3.815 | 49.04 | 2.666 | 54.36 | 0.2183 | 55.66 | 1 |
| 5.5 | 51.11 | 5.469 | 46.74 | 3.858 | 48.64 | 2.668 | 53.76 | 0.2194 | 54.90 | 1 |
| 6.8 | 49.89 | 5.485 | 45.04 | 3.975 | 47.76 | 2.665 | 52.47 | 0.2191 | 53.81 | 1 |

Table 11 shows the calculated average values of speed and PCU values of different vehicle categories to determine the traffic characteristics such as traffic flow, traffic density, and stream speed.

#### *4.7.1 Relationship between traffic density, and mean stream speed*

The speed- density model was developed through traffic characteristics using Excel curve fitting technique and linear equation for all sections. The models are derived with high value of coefficient of determination ($R^2$). The graph of speed and density for all section are presented in following figures.

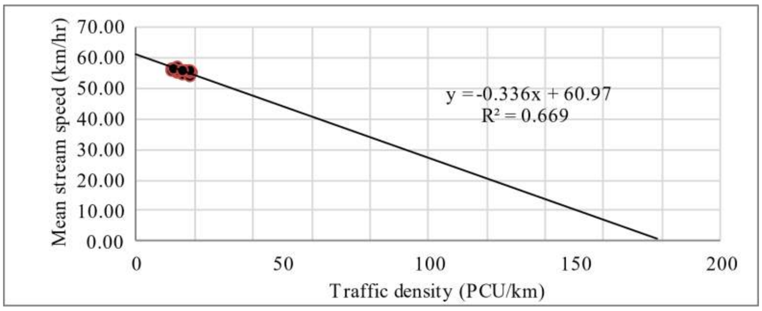


Figure 5. Relationship between traffic density and mean stream speed, Khurkot section

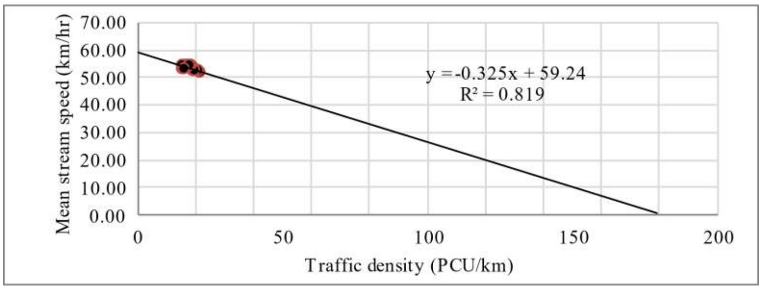


Figure 6. Relationship between traffic density and mean stream speed, Kutunje section

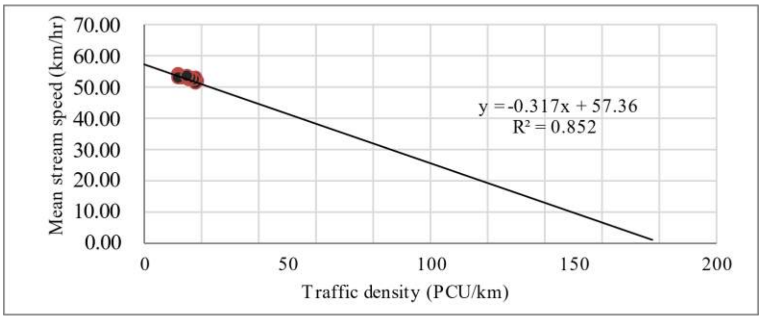


Figure 7. Relationship between traffic density and mean stream speed, Dhulikhel section

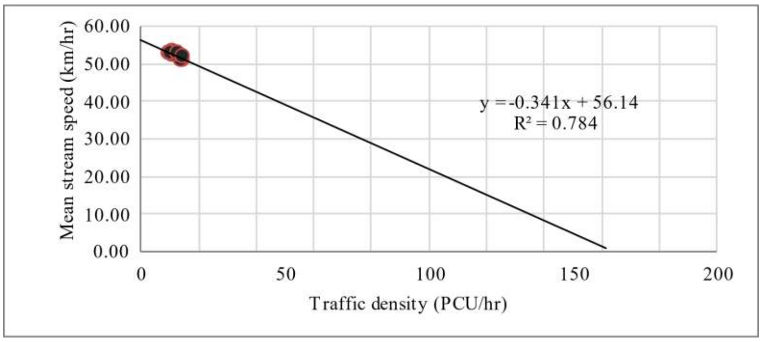


Figure 8. Relationship between traffic density and mean stream speed, Mulkot section

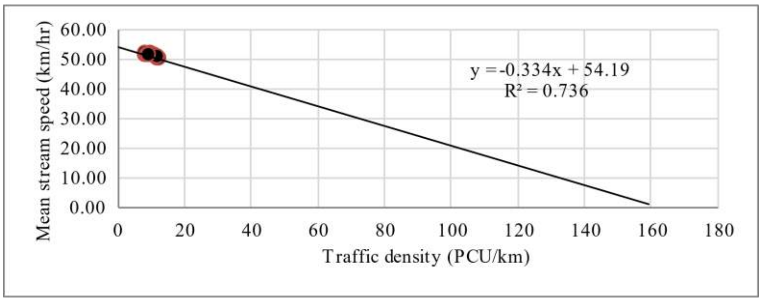


Figure 9. Relationship between traffic density and mean stream speed, Nepalthok section

#### *4.7.2 Summary of roadway capacity*

Based on the observed data points at Khurkot section the capacity of road is found to be 2764 PCU/hr using flow rates of 15-min interval, as given in Figure 5. Similarly the capacity at grade of Kutunje section, Dhulikhel section, Mulkot section and Nepalthok section was found to be 2693 PCU/hr, 2591PCU/hr, 2304 PCU/hr and 2196 PCU/hr respectively. The summary of road capacity value at different grade sections are presented in Table 12.

Table 12. Summary of capacity two-lane undivided carriageway

| S.N | Grade (%) | Capacity(PCU/hr) |
|---|---|---|
| 1 | 2.1 | 2764 |
| 2 | 3.2 | 2693 |
| 3 | 4.3 | 2591 |
| 4 | 5.5 | 2304 |
| 5 | 6.8 | 2196 |

#### *4.7.3 Relationship between capacity and grade*

Capacity values of two-lane undivided roads are correlated with magnitude of gradient. It was found that, capacity of two-lane roads decreases with increase in magnitude of gradient (%). Thus to generalize the effect of magnitude of gradient on capacity, various equations were tried. Simple linear equation found to be the best fit for relationship between capacity (PCU/hr) and magnitude of gradient (%) with linear equation, Capacity = -130.74× Grade(%) + 3082.2. Moreover, $R^2$ value was found to be 0.954, which may be considered satisfactory. It was found that, capacity of highways decreases with increase in magnitude of gradient (%). The relationship between capacity and grade of road is presented in Figure 10.

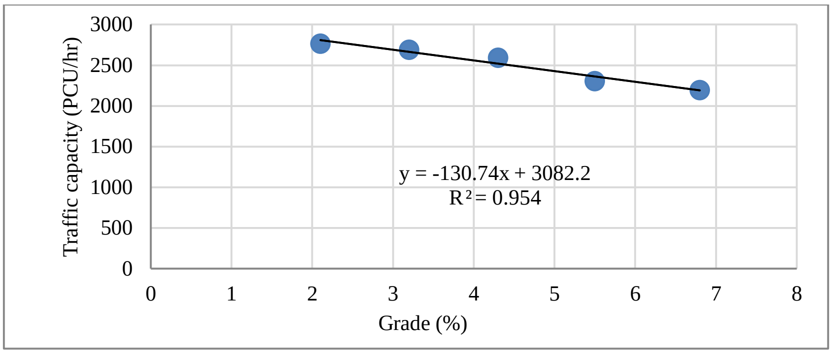


Figure 10. Relationship between capacity and grade of road

Figure 10 shows the relationship between capacity of road and road grade. The roadway capacity for level road obtained from the relationship between capacity and grade is 3082.2 PCU/ hr. While comparing the capacity values of hilly terrain from other countries, capacity values are consistent to the range of capacity values reported by Indo-HCM (3200 PCU/hr for hilly terrain under ideal condition), China-HCM (2300 PCU/h for hilly terrain) and Indonesia-HCM (2900 LVU/h for hilly terrain). Traffic conditions in these countries are more or less similar to Nepalese (heterogeneous) traffic conditions. Hence, the present study developed a new relationship between capacity and road grad (%) based on the observed traffic data sets.

## 5. Conclusion

The present study focuses on detailed methodology of PCU and capacity estimation of two lane undivided hilly roads under heterogeneous traffic condition using fundamental diagrams (Speed-Flow-Density). This study shows that New PCU values obtained from field are much different from those given in NRS 2013 standard. It is found that PCU values obtained for two wheelers are smaller than the values given in NRS 2013 and for Bus, Truck; LCV found higher than the value given in NRS 2013 The study estimates capacity values of two-lane undivided roads for varying magnitude of gradients considering the flow rates 15-min intervals. The capacity of these roads is found to be in the range of 2196 to 2764 PCU/hr for varying magnitude of gradients over a range of 2% to 8%. The study further concludes that, capacity of two-lane undivided hilly roads decreases with increase in magnitude of gradient (%). Thus, capacity estimation is an extensive process starting from detailed road geometric surveys, data collection of actual traffic data, data extraction, and development of fundamental diagrams under prevailing roadway and traffic conditions. However, estimation of operating speeds of different vehicles may be considered less tedious as compared to capacity estimation using fundamental diagrams, as it demands lot of data over full range of traffic flow conditions. This study attempts to develop the relationship between capacity and magnitude of gradient. The relationship is found to be statistically significant.

The geometrical alignment along with the weather conditions also affects manoeuvrability of vehicles on roads in hilly terrain. In the present study, relationships are developed between capacity (PCU/h) and magnitude of grade (Varying over range of 2% to 8%), for road widths 6.75 m to 6.8 m and 0.3 to 0.4 m paved shoulders. In the absence of traffic data over a broader range of traffic conditions, developed relationships can be applied to estimate capacity of two-lane undivided hilly roads having significant magnitude of gradient. Hence, the results presented in this study along with overall methodology may be beneficial for the practitioners to develop Highway Capacity Manual.

6. **Recommendation**

- Speed area method of PCU calculation can be used for hill roads within different location of Nepal to generalize the PCU value instead of using it directly from NRS 2013 (whose PCU is replication from IRC).
- To design new roadway facility for forecasted traffic there should be the proper consideration of gradient for capacity of roadway facility, which changes with road-grade.

**7. Recommendation for further research**

- The studies can be made at intersections, curves and in divided carriageway.
- To calculate PCU only projected area of vehicles were considered, this study may extend our work considering carriageway, roughness and driver characteristics.
- In this work Greenshield's model was used to calculate roadway capacity. This work can be extended for different roadway and traffic condition with suitable methods.

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